Barley bulgur: Effects of drying methods (hot air, microwave, and superheated steam) on cooking qualities, β-glucan fibres, and tocochromanols

By

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Abstract

High β-glucan barley is recognized as a health food. In Europe and North America foods containing barley are allowed to carry a health claim related to the ability of barley β-glucans to reduce cholesterol and the risk of heart disease. Barley, generally, also contains high amounts, by mass, of tocochromanols with a high ratio of tocotrienols. Tocotrienols have been linked to improved health and stronger immune systems.

The objectives of this study were to examine the effects of three different drying techniques on the composition and properties of bulgur prepared from two varieties of high β-glucan barley with different starch characteristics.

A high amylose variety/cultivar *Hordeum vulgare* L. *'CDC Hilose'* and a waxy variety/cultivar *H. vulgare* L. *'CDC Marlina'* (CDC Hilose and CDC Marlina) were cooked in a pressure cooker and subsequently dried using three methods: hot air (convection oven: 50°C, 6 h; 40°C, 16 h), microwave (100 W, 1 min; linear increase in power from 100 to 250 W, 20 min; 250 W, 40 min), and superheated steam at three settings: (110°C, 11 kPa, 2.5 m/s, 60 min), (120°C, 11 kPa, 2.6 m/s, 35 min), and (130°C, 11 kPa, 2.6 m/s, 19 min). The dried barley samples were tested for bulk density, kernel density, 1000 kernel mass, total β-glucans, tocochromanol content (retention), and colour. The samples were then steel cut and sieved to produce two sizes of bulgur; coarse > 2.36 mm and fine $1.18\,\text{mm} < x < 2.36\,\text{mm}$. The size distribution of the

cut barley was analysed and colour values were obtained for both bulgur sizes. The bulgurs were then cooked to gelatinization. Values for cooking time, water absorption, by mass, while cooking, and losses from the bulgur into the cooking water, by mass, were recorded. Concentrations of soluble β-glucans were tested for by cooking the fine bulgur samples and assaying the filtered cooking water for β-glucans.

Generally, the extremes of values were obtained with treatments of superheated steam at 130°C and hot air dried bulgurs. Superheated steam drying at 130°C generated the most friable grain, the lightest colour, the lowest bulk and kernel density values, higher rates of absorption, the lowest amount (w/w) of total β-glucans, and the highest amount (w/w) of soluble β-glucans. In contrast hot air drying generated the least friable grain, with the darkest colour, the highest bulk and kernel density values, the most extended cooking times, and the lowest value for soluble β-glucans (w/w).

Fine bulgur took significantly less time to cook than coarse bulgur, absorbed more water while cooking, and exhibited higher cooking losses. CDC Marlina took significantly less time to cook than CDC Hilose and had significantly more cooking losses. Water absorption was comparable for both varieties. CDC Hilose had significantly more total β-glucans than CDC Marlina (w/w), but CDC Marlina had more soluble β-glucans than CDC Hilose (w/w).

Tocochromanol ratios were best in treatments employing superheated steam at temperatures of 120 and 130°C.

Comparisons, emphasizing the results for β-glucans and tocochromanol ratios demonstrated that drying of barley using superheated steam at temperatures 120 and 130°C produced results that were generally superior to the other drying methods.

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To my lord and saviour, Jesus, I am your creation, and all of this belongs to you. It is written somewhere, "It is the glory of God to conceal a matter; to search out a matter is the glory of kings." To search out a matter academically, to learn, and to strive for more knowledge is an honour bestowed upon us mortals by you, and I am humbled that you have given me this honour. I am by no means a king, and yet you have treated me like one. To learn from you is my joy and life's goal. Please, continue to allow me to search out matters for I have by no means arrived, but I am truly enjoying the journey.

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List of Symbols and Abbreviations

Symbol	**Meaning**
aR^2	Adjusted R squared
ΔE	Delta E
ρ	Density
ϕ	Porosity
AM	Amylose
AP	Amylopectin
ASABE	American Society of Agricultural and Biological Engineers
ATTP	Alpha tocopherol transport protein
CR3	Compliment receptor type 3
CDC	Crop Development Centre
DF	Dietary fibre
DP	Degree of polymerization
DS_T	Degrees of superheat
GI	Glycaemic index
HA	Hot air

Symbol	Meaning
IF	Water insoluble fibre
II	Insulinaemic index
MF	Modulus of fineness
MW	Microwave
rpm	Revolutions per minute
SF	Water soluble fibre
SPF	Supernatent protein factor
SS	Superheated steam
SS_T	Temperature of superheated steam
ST_T	Temperature of saturated steam
T_{SS}	Temperature setting for superheated steam
T	Tocopherol
T3	Tocotrienol
TDF	Total dietary fibre
w/w	Mass for mass (weight for weight)

1. *Background and objectives*

1.1 Background

Currently, barley ranks fourth, in the world, for seeded agricultural land use (Arendt and Zannini 2013). The health benefits of high β-glucan food barley are becoming the focus of increasingly more attention (Ames and Rhymer 2008). Of the grain crops, high β-glucan barleys have the highest levels of β-glucans.

In Canada, barley food products are permitted to contain labels for cardiovascular health claims when the serving size contains at least 1 g of β-glucans (Health Canada 2012). It has been demonstrated that barley β-glucans are beneficial for lowering the peak blood glucose levels postprandial and the dietary fibres in general increase insulin sensitivity (Würsch and Pi-Sunyer 1997; Östman et al. 2006; Regand et al. 2011; Wang and Ellis 2014). Additionally, β-glucans lower LDL cholesterol when ingested at rates of 3 g/d (Ames and Rhymer 2008; Tiwari and Cummins 2011). The benefits of β-glucans also extend to cancer tumour growth retardation and tumour lysis (Cheung et al. 2002). Barley β-glucans have also been demonstrated, in rats, to protect the spinal cord from secondary injury after trauma (Kayali et al. 2005).

In 1986, tocotrienols were isolated in barley and found to be inhibitors of cholesterol

biosynthesis (Qureshi et al. 1986; Sen et al. 2004). Barley oil has relatively high levels of tocotrienols. Research into the health benefits of tocotrienols is growing exponentially (Tan et al. 2012). To date, tocotrienols have been shown to not only act as effective antioxidants, and the list of other health benefits of tocotrienols is extensive: anticancer, cholesterol-lowering properties, protection against neurodegenerative disorders (Alzheimer's disease), anti-angiogenesis, lower risk of secondary infections post influenza infection, anti-atherosclerosis, treatment for dyslipidemia, protection against cardiovascular diseases, protection against UVB damage, radioprotective properties, bone health improvement, and anti-senescence effects (Gay et al. 2004; Kontush and Schekatolina 2004; Sen et al. 2004; Khanna et al. 2006; Berbée et al. 2012; Tan et al. 2012; Viola et al. 2012). Most of the benefits of tocotrienols in the diet are dependent on the right ratio of tocopherols to tocotrienols, and barley, incidentally, has a ratio close to the limits for maximum efficacy (Qureshi et al. 1986; Sen et al. 2004; Berbée et al. 2012; Trias and Tan 2012; Viola et al. 2012).

Bulgur, an ancient food, currently used extensively in Turkey and the Middle East, is a valuable cereal product with good shelf life and exceptional nutritional value (Erba et al. 2016). Bulgur processing generally involves cooking, drying, and cutting. The bulgur product is rehydrated, by cooking, before consumption. Bulgur is most commonly made from durum wheat, but other grains and lentils are also used.

In this study, bulgur was prepared from two varieties of high β-glucan barley: CDC Hilose (high amylose) and CDC Marlina (waxy). For the drying phase of bulgur preparation, three different drying techniques were used: hot air, microwave, and superheated steam. Superheated steam drying was repeated at three temperature settings: 110, 120, and 130°C.

1.2 Objectives

The objective of this study was to examine the effects of three different drying techniques on the composition and properties of bulgur prepared from two varieties of high β-glucan barley with different starch characteristics. The properties considered were; size distribution, colour, bulk density, 1000 kernel mass, kernel density, cooking time, cooking absorption, cooking losses, total and soluble β-glucans, and vitamin E retention values.

2. *Literature Review*

2.1 Preamble

Barley, *Hordeum vulgare L.*, a cereal crop, ranked fourth after corn, rice, and wheat in 2013, in the world, concerning quantity and cultivation area (Arendt and Zannini 2013). Canada is the world's sixth largest producer of barley. In 2014, Canada harvested 7.1 million tonnes (FAOSTAT 2014). In 2017, barley crops occupied 5.8 million acres of Canadian soil (Statistics Canada 2017). Alberta and Saskatchewan account for 90 % of Canada's barley production. Regarding land area, in 2017, barley was the fourth largest crop in Canada.

Canada divides barley into three classes and two types. The three classes are malt, feed, and food. The two types are covered and hull-less barley. Hull-less barley is also known as naked barley. The difference between covered and hull-less types is the strength of adherence of the outer hull; in covered types, the outer hull is still attached after harvesting, whereas, in hull-less types, the outer hull is loosely attached and generally detaches, in the field, during harvest time. Both covered and hull-less types exist in two and six-row varieties. Two-row varieties of barley contain two rows of kernels along their lengths. Six-row varieties of barley contain two sets of three

rows of kernels along their lengths (Canadian Grain Commission 2017).

2.2 Barley kernel structure

Husk and pericarp The structure of the barley kernel consists of several layers surrounding two larger internal sections: the endosperm and the germ. The germ is also known as the embryo. The husk surrounds the kernel. The husk is the outer protective layer of two protective layers; the inner layer is the pericarp. These two protective layers are composed mostly of cellulose, hemicellulose, lignin, and lignans. Mineral proportion is highest in the husk, followed by the embryo and endosperm (Izydorczyk and Dexter 2004). The scutellum separates the endosperm from the germ. The scutellum plays an essential role in mobilizing the reserves of the endosperm during germination. During germination, it elongates, across the aleurone layer and is itself a modified cotyledon (Negbi 1984; Holopainen-Mantila 2015).

Aleurone layer The aleurone layer surrounds the endosperm separating it from the testa. Barley has a multicellular aleurone layer. For classification purposes, Sawicki (1954) found that barleys of Asian origins, as a rule, posses three rows and that those of African origins have two rows. The aleurone cells contain aleurone grains; which are of a globoid geometry and consist of phytins and crystalloids of proteins and polysaccharides. Aleurone cells are high in proteins (17–20 %), triglycerides (20 %), and sugars. During germination aleurone cells release, into the endosperm, α-amylase, phytic acid, and proteases, to catabolize the nutrients stored therein, making them available for the anabolic activities of the embryo (Izydorczyk and Dexter 2004; O'Brien et al. 2010). Aleurone cell walls are 2–5 µm thick. They consist of 26 % β-glucans and

67–71 % arabinoxylans, a form of hemicellulose. Significant degradation of β-glucans in the aleurone cell walls is required before other enzymes, produced in the aleurone cells, can reach the endosperm (O'Brien et al. 2010). At the aleurone-sub-aleurone interface β-(1→3)-glucans, also known as callose, are found (Izydorczyk and Dexter 2004). Additionally, the aleurone and sub-aleurone layers contain tocotrienols, a group of vitamin E (Yoshida et al. 2003). Tocotrienol content in barley ranges from 30 to 67 mg/kg (Peterson and Qureshi 1993).

Endosperm The most substantial part of the kernel is the starchy endosperm, accounting for about 75 % of the barley grain. The endosperm is composed of about 80 % starch, 9 % proteins, and smaller amounts of lipids, minerals, and nucleic acids (Izydorczyk and Dexter 2004). Classifications of starch granules are of two populations; large (A-type) and small (B-type) granules. Typically an inverse ratio of 9:1 can be found between their quantities and mass proportions. The smaller B-type granules outnumber, by nine times, the larger A-type granules, however, the collective mass of the A-type granules is nine times higher than the collective mass of the B-type granules.

Barley can be divided into three genotypes regarding starch compositions, wherein, the two starch structures, amylopectin (AP) and amylose (AM) appear in varying ratios. The three genotypes are normal, waxy, and high amylose. In normal barley varieties, the AP to AM ratio is about 3:1, in waxy from 20:1 to 1:0, and in high amylose the AM portion is higher than in normal genotypes, so that the latter number in the ratio can be as high as 2; *i.e.,* the AP to AM ratio may be 3:2. The cell walls of the starch endosperm consist up to 70 % $\beta-(1\rightarrow3),(1\rightarrow4)$-glucans, 20 % arabinoxylans, and small amounts of proteins, $\beta-(1\rightarrow3)$-glucans, and other polysaccharides. Waxy

and high amylose genotypes consistently have higher proportions of β-glucans than normal starch genotypes (Izydorczyk and Dexter 2004).

Embryo The embryo constitutes about 2.5 % w/w (dry weight) of the barley kernel and is high in protein (34 %), lipids (14–17 %), and ash (5–10 %) (Izydorczyk and Dexter 2004). Tocopherol, vitamers of vitamin E, are found in the embryo (Yoshida et al. 2003). Barley tocopherol content varies from 8 to 15 mg/kg (Peterson and Qureshi 1993). The embryo is exceptionally rich in sugars (20–25 %) with sucrose accounting for 15 % and raffinose 5–10 %. Fructosan sugars are also present in the embryo (Izydorczyk and Dexter 2004). During germination, the endosperm releases gibberellins which are blocked by the scutellum and are, thereby, forced into the aleurone layer (O'Brien et al. 2010). Gibberellins activate, in the aleurone cells, the production of enzymes that support the germination process.

2.3 Barley kernel composition

Barley is rich in phenolic compounds including polyphenols, phenolic acids, proanthocyanidins, and catechins (Thondre et al. 2012). Barley varieties can be bred for higher or lower levels of various components including, but not limited to, β-glucans, starch composition, and dietary fibre. Table 2.1 lists the more prominent constituents of barley kernels with typical ranges and those for Prowashanupana variety, which has high β-glucans content.

Table 2.1: General constituents of whole barley and for Prowashanupana variety in percentages w/w.

	Component	Percentage of whole barley (% w/w)		
		Range		Prowashanupana
		Lower	Upper	
1	Starch	62	77	64
2	Protein	10	17	18
3	Dietary fibre (DF)[*1]	11	34	30
4	Soluble fibre (SF)[*2]	3	20	12
5	β-glucans	4	9	17
6	Free lipids	2	3	6.5
7	Minerals	1.5	2.5	0.5

Adapted from Thondre et al. (2012) and Gao et al. (2015)
[*1] Includes β-glucans
[*2] Percentage of DF

2.4 Dietary fibre

Dietary fibre (DF) is that portion of the total carbohydrates which remains undigested after passing through the small intestine (Ranhotra and Gelroth 2001). Dietary fibre is divided into two categories: water-insoluble fibre (IF) and water-soluble fibre (SF) (Ranhotra and Gelroth 2001; Thondre et al. 2012; Park et al. 2013). When referring to both IF and SF the term total dietary fibre (TDF) is used. Dietary fibre is sourced solely from plant-based foods, and for adults, the recommended daily intake is 25 g. The benefits of dietary fibre include protective effects against select cancers and cardiovascular diseases (Ranhotra and Gelroth 2001). Barley DF, in particular, has been shown to increase insulin sensitivity, raise levels of satiety hormones, promote mitochondrial fat oxidation, and, in rodents, has been demonstrated to increase energy expenditure and decrease fat accretion (Gao et al. 2015).

Moreover, DF in food often results in a caloric reduction in diets as DFs often replace fat. Carrageenan, β-glucans and curdlan, are several fibres used in the food industry, to replace fats. Other benefits of DF for the food industry include properties of anti-caking, anti-sticking, dimensional stabilizing effects, texturing, and gelling (Ranhotra and Gelroth 2001; Yotsuzuka 2001; Ryu et al. 2012; Zhao et al. 2015). Some of these properties such as anti-caking and anti-sticking assist in the food preparation process, whereas, others such as the properties of texturing and gelling aid also in palate appeal to the consumer. Additional benefits of DF, specifically β-glucans, incorporated into foods include increased shelf life (Sánchez-Madrigal et al. 2015).

Barley Fibre Barley kernels have high proportions of fibre throughout. The hull and pericarp contain cellulose. The cell walls of the aleurone layer and the starchy endosperm have a high content of arabinoxylan and β-glucans. When averaged, naked varieties have less TDF than hulled varieties, but their β-glucans content is higher.

2.5 β-glucans

Structure β-glucans are polymers of β-D-glucopyranose molecules, found in the cell walls of various fungi, yeasts, bacteria, and cereals, such as oats and barley. The structure of non-cereal β-glucans are a $(1 \rightarrow 3)$ backbone which may or may not have longer or shorter (1→6) branching (Lowman et al. 2011; Zheng et al. 2016). β-D-glucans originating from cereals, in particular, barley, are mixed (1→3,1→4)-β-D-glucans. Barley β-D-glucans contain both water soluble and water insoluble chains (Izydorczyk and Dexter 2008; Mikkelsen et al. 2013). For barley β-glucans, the (1→4) linkages repeat themselves with a single (1→3) linkage between the (1→4) polymerization. The

degree of polymerization (DP) of (1→4) linkages between the single (1→3) linkages varies, however, 90–95 % of DP are less than 5 units long, and the remainder are from 5 to 28 units in length (Izydorczyk and Dexter 2008).

Variation amongst varieties Barley β-glucans content varies substantially amongst different varieties, and within a particular variety significant differences are noted when cultivated within different climates (Fastnaught 2001). It is also noted that hull-less varieties of barley generally contain higher levels of soluble β-glucans than hulled varieties (Ames and Rhymer 2008).

2.5.1 Health claims of barley β-glucans

Diabetes mellitus Östman et al. (2006) studied the effect of barley bread with different concentrations of β-glucans on healthy men. The authors used bread with three different concentrations of β-glucan-rich barley (35, 50, and 75 %), as well as common barley (50 % concentration) and a 100 % wheat bread control. The authors found that bread containing 50 and 75 % barley flour led to decreases of 40 and 48 %, respectively in the breads glycaemic index (GI) value when compared with a wheat flour bread control. The insulinaemic index (II) was also found to decrease by 37 and 34 %, respectively. The authors concluded that the incorporation of β-glucan rich barley fractions into bread might lower both the GI and II properties of the bread. Regand et al. (2011) found that β-glucans (soluble) lowered the human glycemic response by modifying the starch digestibility and that a ratio of 0.16:1 β-glucans to starch was more effective than a lower ratio of 0.11:1. The same study also found that molecular weight was a significant factor and that the presence of β-glucans in the ingredients might interfere with the gelatinization process of starch during baking.

Although this is not the only pathway through which they work, it is significant to note that the ratio of β-glucans to starch for a given meal is a factor, whereas for other health benefits the total consumption per day was found to be the necessary factor (Ames and Rhymer 2008). Wang and Ellis (2014) found that viscosity was at least one of the pathways through which β-glucans lowered blood glucose levels. While true that all soluble fibres will contribute to gastrointestinal viscosity and subsequently can lower the GI of a meal, β-glucans have been found to be the most effective. When β-glucans are incorporated into a meal at 8–10 %, the glycaemic peak may be lowered by up to 50 % (Würsch and Pi-Sunyer 1997).

Cardiovascular Health Canada (2012) concluded that barley β-glucans reduce/lower LDL-cholesterol, thereby, allowing health claims on barley food products. To qualify, under this provision, certain requirements must be met. One of these requirements is that the food must contain at least 1 g of β-glucans per serving size. Wang and Klopfenstein (1993) found that a high viscosity diet lowers serum cholesterol, in rats. Experimentation was done using wheat, oat, and barley grain diets. The grains were fed raw, or prepared using extrusion at three different speeds. The study found that a barley diet was more effective at lowering blood serum cholesterol and that extruded barley diets had the lowest serum cholesterol levels coupled with the lowest levels of liver cholesterol. Barely β-glucans improve cardiovascular health by lowering LDL cholesterol with dosages as low as 3 g/d (Ames and Rhymer 2008; Tiwari and Cummins 2011).

Antioxidant Kayali et al. (2005) examined the soluble β-glucans as an antioxidant agent in spinal cord injury in rats. The results showed that β-glucans protected from

secondary injury after trauma. The suggested mechanism for this phenomenon is a receptor on macrophages for the $\beta-(1\rightarrow 3)$-D-glucan molecule. The authors conclude the study by calling for further study on the ability of β-glucans to act as agents for neuroprotection in spinal cord injury.

Immunology and oncology It has been noted that soluble β-glucans are removed from the small intestine and attach to the complement receptor type 3 (CR3) of leukocytes (Thornton et al. 1996), stimulating immune system response and aiding natural killer cells' ability to lyse tumour cells, otherwise resistant to cytotoxicity (Vetvicka et al. 1996). Agrawal et al. (2010) found that β-glucans stimulate human dendritic cells priming Th17 and cytotoxic CD8 T cell expressing Granzyme B and perforin. The authors propose that this explains the effectiveness of β-glucans for cancer treatment. Cheung et al. (2002) found that β-glucan primed leukocyte CR3 worked in synergy with monoclonal antibodies for cancer tumour growth retardation and tumour lysis.

2.6 Vitamin E

Vitamin E was first discovered in 1922 as a component necessary for reproduction in rats (Evans and Bishop 1922). Naming of the discovered molecule (tocopherol) as vitamin E happened several years later. It took approximately another 40 years till the discovery that vitamin E consists of numerous distinct variations with naming and renaming taking place as new vitamers were discovered (Pennock et al. 1964). Presently, it is generally understood that vitamin E is composed of eight lipid soluble vitamers, including four tocopherols (T for singular, Ts for plural), with 16 carbon

saturated phytyl side chains, and four tocotrienols (T3 for singular, T3s for plural), with 16 carbon unsaturated isoprenoid side chains with 3 double bonds. According to the functional groups on the tocochromanol heads they are classified as α, β, γ, δ (Figure 2.1). However, two more decades passed before it became increasingly evident that the two variations in the lipophilic tails did not play equal roles in human health, bioavailability, nor bioactivity (Qureshi et al. 1986).

Additionally, the differences in the chromanol heads have distinct roles and pecking orders in bioavailability and bioactivity. Kamal-Eldin and Appelqvist (1996) reported that literature concerning T3s was scant. More recently, an ever-increasing amount of attention is being directed to the functional roles of the T3 group and the discrepancies between the activities of the T3 and T groups. At the time of this writing, the majority of the literature reviewed introduced vitamin E as a group of eight vitamers with four Ts and four T3s. Several authors worded their introduction of vitamin E as a group of at least eight vitamers, including four Ts and four T3s. Recently, claims have been filed that vitamin E also includes a tocomonoenol group (Fiorentino et al. 2009; Butinar et al. 2011). Studies related to tocomonoenols are scant. This scarcity may be due to their possible rarity in nature, as well as, the relative novelty of their discovery.

2.6.1 Vitamin E as an antioxidant

Free radicals in the body play a beneficial role during phagocytosis, however, in healthy cells they are a liability, damaging DNA, and responsible for lipid peroxidation. Various internal mechanisms, such as enzymes, inhibit oxidation by eliminating species responsible for producing free radical chain reactions. Secondary defences against oxidation reduce the oxidizing radicals and are thereby labelled as chain-breaking

antioxidants (Buettner 1993).

Vitamin E functions as a chain-breaking antioxidant preventing the cyclic propagation of lipid peroxidation (Mustacich et al. 2007). According to mathematical modelling, one T molecule can protect approximately 1000 lipid molecules. Each chromanol head (tocopherol) donates two electrons as an antioxidant after which it remains in the cell wall close to the lipid-water interface as a relatively stable molecule. The reduced chromanol head (tocopherol) can be regenerated by vitamin C and other aqueous antioxidants (Buettner 1993; Kostner et al. 1995). Enzymes accomplish the regeneration of vitamin C through natural biological processes (Buettner 1993).

Antioxidant activity based on tail configuration Yoshida et al. (2003) examined the antioxidant activities of the eight vitamers. They found no difference between the classes of tails, nor between their mobility within cell membranes. However, T3s displayed heightened mobility between adjacent cell membranes over Ts. Saito et al. (2010) examined the antioxidant activities of the eight established vitamers against glutamate-neuronal cell death, in-vitro, and found that, under identical concentrations, T3s were more effective than Ts in co-treatment trials, however, in pretreatment trials the difference was less profound. The explanation for this phenomenon was that T3s are absorbed more readily into cell walls than Ts, although, when considering in cell concentrations the difference may be non-existent. In-vivo, however, T3s are poorly transported throughout the body indicating that Ts may, therefore, play a more dominant anti-oxidative role than T3s. Suzuki et al. (1993) found that α-T3 resided closer to the membrane surface than α-T and that this was the underlying explanation for its higher efficacy as an antioxidant.

Antioxidant activity based on chromanol head configuration Attempts have been made to give a ranking order to the antioxidant activity of the four variations of chromanol heads. Tan and Brzuskiewicz (1989) reported that polarity decreases with increasing methyl groups. Indicating that δ-T/T3 are the most polar and that α-T/T3 are the least polar, amongst the established vitamers. According to the polar paradox theory, nonpolar antioxidants are more potent in polar media, whereas, polar antioxidants are better suited for nonpolar media (Zhong and Shahidi 2011). As vitamin E is a lipophilic antioxidant, this theory would suggest that δ variations are more powerful antioxidants than α variations. Results from experiments conducted by Saito et al. (2010) demonstrated that the rescue rate of vitamin E isoforms against glutamate-neuronal cell death at low doses with pretreatment confirmed this theory, whereas, at high doses, with pretreatment, the opposite was found. Zhong and Shahidi (2011) illuminated the polar paradox theory using polar, nonpolar antioxidant pairs, within the parameters of conjugated dienes. Findings from that study pointed to a critical concentration undulation point. Concentrations above this point failed to reject the polar paradox theory, whereas, concentrations below the critical point rejected the hypothesis. Thus, it is difficult to assign a hierarchy to the groups as an antioxidant. Therefore, an examination of the non-anti-oxidative benefits of vitamin E may be more beneficial for establishing a pecking order of efficacy.

2.6.2 In-vivo transport of vitamin E

Vitamin E has eight distinct vitamers with four variations in the chromanol head and two variations in the tail. The transport mechanism in humans appears to be limited to the α-T transport protein (ATTP) and the supernatant protein factor (SPF). Both

SPF and ATTP are cytosolic lipid-binding proteins (Porter 2003). They share a greater relative affinity for α-T 100 %, followed by 38, 9, and 2 % for β, γ, and δ T, respectively. The relative affinity of ATTP for α-T3 is 12 % of that of α-T, with the remaining T3s displaying a virtually negligible affinity for ATTP (Hosomi et al. 1997; Yang et al. 2012). The lack of an effective natural carrier for non-α-Ts and T3s has been shown to hinder their distribution to cells and catalyzing their metabolism and discharge from the body (Ikeda et al. 2003; Ikeda et al. 2012). Transport to and concentrations of T3s in cells is, therefore, dependent on restricting the vitamin E mixture to one containing less than 15 % α-T, which has been shown to enhance the bioavailability of T3s greatly and hence their bioactivity (Trias and Tan 2012). Incidentally, barley contains a mix where more than 70 % of the vitamers are T3s (Qureshi et al. 2002).

Bioavailability and bioactivity Saito et al. (2010) demonstrated that as an antioxidant for protection against glutamate-induced neuronal cell death T3s at concentrations of 0.25 µM were generally as potent and sometimes more so than their T counterparts at concentrations of 2.5 µM. Whereas, α-T has a higher bioavailability the T3s posses higher bioactivity at lower concentrations. Nevertheless, this differentiation in literature is often omitted. α-T is often reported as the most bioactive vitamer of vitamin E. With rare exceptions α-T is the least bioactive vitamer, when measured at equal concentration levels, nonetheless, it is the most bioavailable.

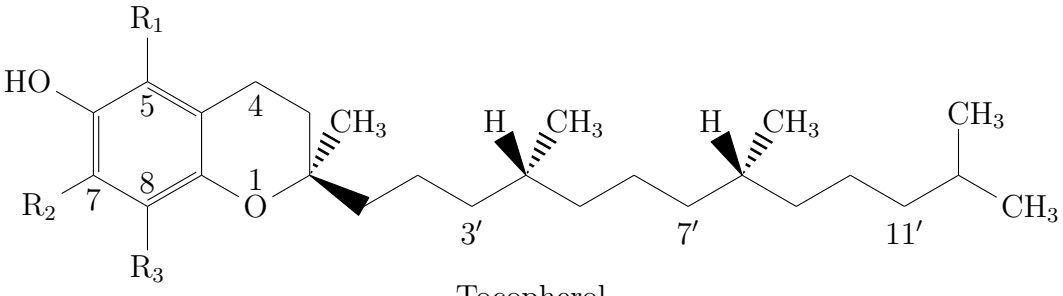
2.6.3 Tocotrienols as pro-health agents

Since at least 1986, when T3s were isolated in barley and found to be inhibitors of cholesterol biosynthesis, T3s have increasingly been the focus of attention as

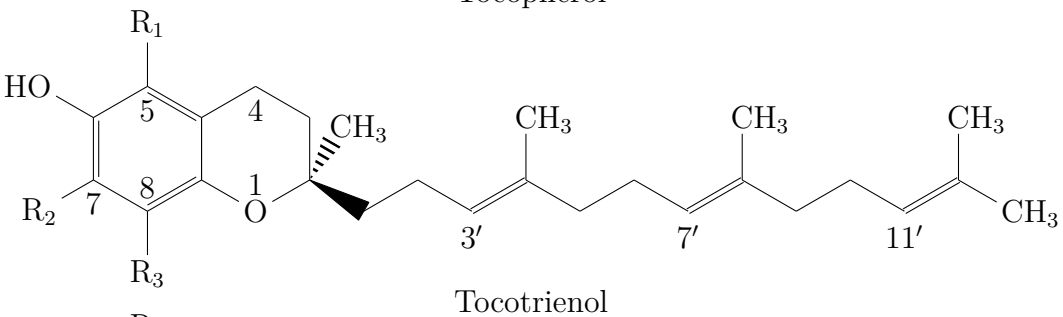
agents of health beyond direct antioxidant behaviour (Qureshi et al. 1986; Sen et al. 2004). Vitamers of vitamin E have been studied for their non-antioxidative properties including; anticancer, cholesterol-lowering properties, protection against neurodegenerative disorders (Alzheimer's disease), anti-angiogenesis, lower risk of secondary infections post influenza infection, anti-atherosclerosis, treatment for dyslipidemia, protection against cardiovascular diseases, protection against UVB damage, radioprotective properties, bone health improvement, and anti-senescence effects (Gay et al. 2004; Kontush and Schekatolina 2004; Sen et al. 2004; Khanna et al. 2006; Berbée et al. 2012; Tan et al. 2012; Viola et al. 2012). The overwhelming consensus amongst available literature is that whenever there is a difference in efficacy T3s are better than Ts and that less methylation in the chromanol heads is more effective, in particular, that methylation of the R1 group is the best indicator of less efficacy, thus, $\delta \geq \gamma > \beta \geq \alpha$ is the hierarchy for pro-health activity (Qureshi et al. 1986; Sen et al. 2004; Berbée et al. 2012; Trias and Tan 2012; Viola et al. 2012). Incidentally, several of those studies also found that α-T often attenuated the pro-health benefits of T3s. Berbée et al. (2012) studied the regulation of gene expression of endothelial cells by α-T, γ-T, and γ-T3 to elucidate why γ-T3 were so superior to the other vitamers in providing radioprotective properties. They found that γ-T3 regulated 898 genes, γ-T affected 172 genes, whereas α-T influenced only 39 genes. Moreover, the study also found that overlap was minimal and when considering gene clusters γ-T3 regulated 223 functional clusters not regulated by either γ-T or α-T.

Alternatively, vitamin E can be classified as a benzene ring with a 20 carbon tail: the T3 group possesses a 20-carbon-geranylgeranyl tail, whereas, the T group has a 20-carbon-phytyl tail (Prasad et al. 2012, Section 15.2). Ohizumi et al. (1995)

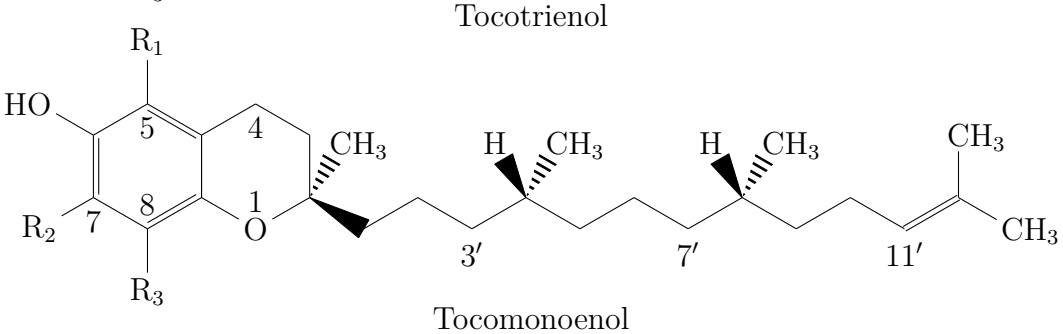
studied various isoprenoids at a concentration of 50 µM for inducers of apoptosis for human leukemia HL-60 cells and found that polyprenyl alcohols with a geranylgeranyl group had the highest potency for inducing apoptosis in the mentioned cancer cells. Although no connection between the two studies mentioned above was found in the existing literature, this connection may help explain why T3s exhibit anti-cancer traits but Ts do not.



Tocopherol



Tocotrienol



Tocomonoenol

Methylated positions	**Tocopherol**	**Tocotrienol**	**Tocomonoenol**
5,7,8-Trimethyl (R_1,R_2,R_3)	α-T	α-T3	(α-T1) Butinar et al. (2011)
5,8-Dimethyl (R_1,R_3)	β-T	β-T3	
7,8-Dimethyl (R_2,R_3)	γ-T	γ-T3	(γ-T1) Butinar et al. (2011)
8-Monomethyl (R_3)	δ-T	δ-T3	(δ-T1) Fiorentino et al. (2009)

Figure 2.1: Molecular models of vitamin E structures. Tocopherol (T) and tocotrienol (T3) groupings of vitamin E are well established in literature. Tocomonoenol (T1) vitamers are novel with no known reported cases of (β) 5,8 methylation.

2.7 Bulgur

Bulgur, an ancient food, currently used extensively in Turkey and the Middle East, is a valuable cereal product with good shelf life and exceptional nutritional value (Bilgiçli 2009; Caba et al. 2011). Most commonly, bulgur is made from durum wheat. However, a plethora of other crops are also used for bulgur production; barley, oats, corn, triticale (a hybrid of wheat and rye), barley, rye, soybean, and chickpeas are listed as crops that have been made into bulgur (Köksel et al. 1999; Bilgiçli 2009). Bulgur preparation involves cooking, drying, and comminution. For beans, a presoak is often used before cooking. Comminution may involve rolling, steel cutting, pearling, grinding, or any combination of these methods. The final product is quickly prepared as the starch previously gelatinized in the cooking step is quickly rehydrated, making an end product that is easy to prepare. Furthermore, the starch in the bulgur product is retrograded, reducing its digestibility, and therein lengthening its shelf life (Erba et al. 2016). The cooking, drying, comminution methods used and their combinations may significantly alter the colour, yield, chemical composition, nutritive quality, physical properties, the content and solubility of β-glucans, and the retention of vitamin E vitamers in the end product (Köksel et al. 1999; Bilgiçli 2009; Erta and Türker 2014; Savas and Basman 2016).

2.8 Drying methods

2.8.1 Hot air drying

Hot air drying may well be the oldest and most common form of drying food products. As air with low relative humidity is forced past wet substrates moisture will be removed from the saturated boundary layer. The resulting moisture gradient will move water through the substance to the outer layer where the low vapour pressure results in a phase change to replenish the boundary layer of moisture-saturated air. The thickness of the boundary layer for a drying substance is not a steady state but rather a function of air movement, temperature gradient, moisture content, and thermal conduction properties of the substrate. After the outer layer of moisture has been dried the rate of drying is limited to the moisture diffusion rate of the substance.

2.8.2 Microwave (MW)

Microwave drying employs electromagnetic waves in the microwave region. These light waves excite polar molecules in the substance, causing them to rotate creating thermal energy. Water is a polar molecule. Therefore, the moisture in the substance will be heated directly. Non-polar molecules are heated through conduction. The water expands as the temperature rises and boiling results. The newly formed vapour diffuses into the atmosphere. If water vapour evolves beneath the surface layer a more porous and brittle material would be expected. Pu et al. (2016) studied MW drying rates and their effects on quality with varying air convection rates, as well as varying humidity levels. They found that higher relative humidity (RH) of the surrounding air

resulted in lower drying rates. After drying, they rehydrated the carrots and tested their quality. A panel of 9 judges evaluated the rehydrated products based on their perceptions. Higher levels of RH, while drying, were found to produce significantly superior results when applying criteria of odour, shape, taste, and textural consistency. Silva et al. (2016) found that MW drying was effective at disinfestation of Brazil nut seeds. Microwave treatment and drying do not produce uniform heating, which can damage the product in localized spots of overheating and undertreat localized cold spots (Song et al. 2016). To overcome the challenges of non-uniform heating combined thermal and microwave driers have been proposed (Song et al. 2016).

2.8.3 Superheated steam

Overview

Superheated steam (SS) is a phenomenon that occurs when the temperature of the steam is raised in an isobaric environment above the saturation temperature, or when saturated steam drops in pressure in an isothermic setting. In either case, enthalpy rises beyond the enthalpy of saturated steam at that pressure. For the current study, elevated temperatures were used.

By examining a pressure-enthalpy chart for water, several observations can be made. Degrees of superheat (DS_T) is the difference between the superheated steam temperature (SS_T) and the saturation temperature (ST_T) for steam at a given pressure; thus, $DS_T = SS_T - ST_T$. When SS comes into contact with the wet product the temperature, and enthalpy, of the SS decreases. Initially, this happens as the moisture in the material is brought to a state of saturated steam (latent heat). Afterwards, the water from the product will itself become superheated and increase in temperature

(and enthalpy) until equilibrium is reached. During this period of equilibration, the temperature of the SS drying medium loses enthalpy, and its temperature continues to decline (sensible heat).

Drying with SS can be done at reduced pressure (vacuum), atmospheric pressure, or elevated pressure (pressurized). Assuming a constant temperature and velocity for SS, reduced pressure offers less mass flow, whereas increased pressure offers a lower DS_T. Elustondo et al. (2002) developed a mathematical model, to determine the criterion for optimum pressure for drying foodstuffs with SS under reduced pressure conditions. They validated their model experimentally with SS velocity of 2 m/s showing that for a set SS temperature range from (60 to 90°C) an optimum drying rate can be obtained by precisely choosing the correct pressure setting for the selected temperature. Below the optimal pressure, the lack of mass flow of SS results in slower drying and above the optimal pressure a lack of DS_T results in a slower drying rate. As the temperature point of SS is raised so too is the corresponding optimal pressure (Elustondo et al. 2002). Superheated steam drying can take advantage of heat transfer through both mass flow and radiant heat flow (Sheikholeslami and Watkinson 1992). Sano et al. (2005) reported that the contribution of radiation heat transfer increased with reduced pressure, although the method used may have included some residual air.

Superheated steam can be used for simultaneous processing of food products while drying. Pronyk et al. (2008) and Pronyk et al. (2010) experimented with drying Asian noodles made from wheat flour and reported simultaneous gelatinization of starch with drying.

Superheated steam drying involves four stages when the product is introduced at a

temperature below the saturated steam temperature; 1) condensation phase, 2) recovery phase, 3) constant rate drying period, 4) falling rate drying period (Iyota et al. 2001). When the temperature of the material is above the saturated steam temperature then only phases three and four are encountered. During the condensation phase, SS condenses on the material releasing into the material the latent heat of vaporization resulting in a rapid rise in temperature of the material. During the recovery phase, the condensed water returns to the state of SS. The constant rate drying period removes the free moisture and finishes at a critical point after which the falling rate drying period continues the process until all moisture is removed. Moisture in the material evolves into steam at whichever point it attains the saturation temperature. The newly evolved steam does not diffuse into the drying medium and can, therefore, occur beneath the surface layer. This evolution of steam beneath the surface layer results in increased porosity and decreased strength because of flash evaporation (Devahastin et al. 2004; Pronyk et al. 2008; Pronyk et al. 2010). Higher processing temperatures of SS have been associated with higher porosity of the final product and its lower strength. Conversely, lower temperatures often with reduced pressures have been linked to higher quality products (Devahastin et al. 2004; Pronyk et al. 2008)

Differences between SS and hot air drying

For SS drying the rate-limiting factor is heat transfer, as there is no diffusion between the newly formed gas and the drying medium, whereas, during hot air drying the rate-limiting factor is diffusion (Shibata and Mujumdar 1994). The differences in these rate limiting factors favour hot air drying at lower temperatures but SS drying at elevated temperatures. The temperature at which these rate-limiting factors cross from

favouring hot air drying to SS drying is defined as the inversion temperature (Kudra and Mujumdar 2009, Section 7.2). Shibata and Mujumdar (1994) demonstrated that when comparing SS drying to hot air drying an inversion temperature can be found when maintaining an equal mass flow rate. Below the inversion temperature, hot air drying produces a faster drying rate, whereas, above the inversion temperature, SS drying is favoured. It would make for a fascinating study to re-examine these findings with an emphasis on enthalpy flow rates rather than on the mass flow rate. In most studies, reviewed, comparing SS and hot air drying an emphasis was placed on comparing drying rates or product quality while maintaining identical mass flow rates or velocities. However, not a single study was found wherein an emphasis was placed on maintaining enthalpy flow rates.

Superheated steam has an affinity for moisture and has several advantages over hot air drying, including lower net energy consumption through recycling of exhaust steam and improved product quality (Björk and Rasmuson 1995). Urbaniec and Malczewski (1997) examined the use of SS for drying beet pulp in Poland and found that substantial savings were attainable as an adequately configured plant could reuse 90 % of the energy input for the drying process. As SS drying is done without the presence of oxygen, this often results in product quality improvement and simultaneously removes the aspect of a fire hazard. Additionally, Urbaniec and Malczewski (1997) reported that a two-stage SS drying system was economically advantageous over a single stage SS drying system. For their system, the first stage employed fluidized-bed drying and the second stage used stationary bed drying, with agitation.

Hot air dryers are less complex with lower initial capital cost than SS drying systems. However, SS drying involves less energy consumption and often results in a

better product with less risk of explosion and fire (Pronyk et al. 2010). Furthermore, SS drying is often faster than hot air drying allowing for smaller drying systems. The savings from less energy consumption and smaller equipment setups can range from 50 to 80 % (Pronyk et al. 2004).

3. *Materials and Methods*

3.1 Pre-treatment

Barley, of two varieties, CDC Hilose and CDC Marlina was obtained from Tomtene Seed Farm. The barley was grown in Western Canada in 2015. As a pretreatment the barley was cooked in a pressure cooker (Instant Pot, IP-DUO60; Ottawa, Canada) at 70 kPa (gauge), 115.4°C for 15 min in tap water. (Settings were set to "Multigrain" and "High Pressure" with 15 min of cooking time.) For cooking, 1.5 L of water was used. The max amount of grain for a cooking session was 500 g. After cooking the samples were removed from the pressure cooker and excess water was discarded. Paper towels were used to absorb free water until the mass of cooked sample was about twice the mass of the precooked sample. The cooked samples were subsequently dried using one of the following three methods; hot air (HA), microwave (MW), and superheated steam (SS). For SS drying the process was repeated using three temperature settings: 110, 120, and 130°C. The drying techniques are further detailed in Section 3.2.

3.2 Drying treatment

All drying treatments were done with the goal of achieving an end moisture content of 9 % wet basis.

3.2.1 Microwave drying

About 40 g of pressure cooked samples, as described in Section 3.1 (Pre-treatment), were placed in four glass Petri dishes (about 10 g/dish) on a rotating tray in a microwave (Multiwave 3000 equipped with Rotor 1Dry, Anton Paar; Ashland, VA). Settings were configured to 100 W for one min, followed by a steady increase in power from 100 to 250 W for 20 min, constant power at 250 W for 40 min, and 30 min of cooling time with no power.

3.2.2 Hot air drying

Two trays with about 500 g/tray of pressure cooked samples, as described in Section 3.1 (Pre-treatment), were placed in a convection oven (Easy Touch, Convotherm by Cleveland, Cleveland Range; Cleveland OH) set to 50°C for 6 hours then 40°C for 16 hours.

3.2.3 Superheated steam drying

Superheated steam unit The superheated steam drying unit is described in detail in the work of Bourassa (2015). Several modifications were made to the unit after Bourassa completed his work. The modifications were made to reduce thermal losses, to enhance safety for the operator, and to increase the SS mass flow rate. Firstly, the

adiabatic processing chamber was insulated to reduce pre-heat times and improve safety considerations for the operator. Secondly, the electronic scale was removed from above the chamber requiring the sample to be removed for weighing. The hanging tray was replaced with a nested tray to facilitate larger sample sizes, making the use of the scale impossible. Removing the scale eliminated insignificant SS losses but significantly reduced noise levels. Thirdly, a second boiler was added in parallel with the pre-existing one. The second boiler served to increase the SS mass flow rate.

The unit designed and fabricated at the University of Manitoba supplies superheated steam to the adiabatic processing chamber. The process flow for the SS system is as follows: Water is supplied from a reservoir (1) via two centrifugal pumps (2) working in parallel to two boilers (5). The boilers bring the water to a state of saturated steam at a pressure higher than atmospheric. The max setting for the boilers is 80 psi (550 kPa). The saturated steam from both boilers is joined via piping. The saturated steam passes through a pressure reducing valve (7), after which it is superheated in a flange superheater (9). With the gate valve (8) fully opened to allow for max mass flow rate, the boilers were able to maintain about 20 psi (140 kPa) working pressure, which has a corresponding saturation temperature close to 126°C. After passing through the pressure reducing valve the pressure of the steam is close to atmospheric and its temperature close to 120°C, however, the corresponding saturation temperature is closer to 100°C. The steam is now superheated with about 20°C superheat. The steam thereafter passes through a superheater (9) where it is heated. The addition of heat raises the temperature and pressure (by constricted expansion). The additional heat of the superheater compensates for future losses encountered in the system and raises the temperature if required. A three-way valve

(10) directs the steam either through the drying chamber (11) or back to the reservoir (1), via a sparge pipe (15). Steam enters the drying chamber (11) through the back where it is directed through a circular tube and subsequently through the sample tray (Figure 3.2). The steam exists through the back of the drying chamber near the top and is piped through a heat exchanger (12) where it is condensed to water. The heat exchanger is cooled using tap water (16) which is drained (14) after a single pass through the heat exchanger. The condensed steam is directed to a three-way valve (10) where it is either returned to the reservoir (1), via the sparge pipe (15) or directed to a second three-way valve (10) where it is either directed to an open pipe (13) or drained (14) Figure 3.1.

Sample placement The cooked sample, as per Section 3.1 (Pre-treatment), was placed at the top of the steam exit within a container made from an aluminum collar with a stainless steel mesh bottom and a glass cylinder. The diameter of the bottom of the collar, where steam enters the sample, was 81.3 mm. The mesh was woven stainless steel with a square aperture width of 1.00 mm and a wire thickness of 0.35 mm. The glass tube extending above the aluminum tray had a height of 75 mm and an inside diameter of 85.0 mm. The tube itself was cut from a 600 mL Pyrex beaker (Figure 3.2). Steam temperature and pressure were measured just before encountering the sample (Figure 3.3). The superficial velocity of the steam passing through the sample was (2.62 ± 0.26) m/s for treatments at 130°C, (2.57 ± 0.20) m/s for treatments at 120°C, and (2.52 ± 0.12) m/s for treatments at 110°C (measured using the inner diameter of the glass cylinder 85.0 mm, where $\pm$ is 1 standard deviation). For homogeneous single layer drying, the sample size was limited to approximately 100 g or less. The drying process was partially fluidized with occasional bubbling during the early phases of

drying. Fluidization of the sample was not by design but rather an observed outcome of increasing the mass flow rate. A screen was not placed above the sample, to restrict losses upon initial exposure to high velocity, as the fluidization effect was not observed until near the end of experimentation. The barley was periodically removed for weighing, to monitor progress, and stirring, to ensure uniform drying. The process was considered complete when the moisture content (mc) reached about 9 to 10 % (wet basis). This process was repeated at steam temperature settings of 110, 120, and 130°C.

Determination of superheated steam velocity Steam velocity is a function of mass flow rate, specific volume, and area (Equation 3.1). The mass flow rate was determined by placing a 1 L beaker under the open pipe (11) (Figure 3.1) and timing the flow of condensate until 1 L was obtained. The condensed steam after the heat exchanger was close in temperature to tap water (about 10°C). At 10°C the density of water is 1.0 g/cm^3. Therefore, 1000 cm^3 was taken as 1 kg for measuring the mass flow rate of condensate. The area was determined as the cross-sectional area of the beaker holding the sample (0.005 645 m^2). Specific volume was determined by using an online tool, courtesy of Spirax Sarco (2018), where the values of pressure and temperature of the SS are entered, and values corresponding to the remaining properties are returned. Of interest to this study was the value for specific volume for the calculation of steam velocity.

$$V = S \cdot \dot{m} \cdot \frac{1}{A}, \tag{3.1}$$

where V is steam velocity in m/s, S is the specific volume of steam in m^3/kg, $\dot{m}$ is the mass flow rate of steam in kg/s, and A is the area in m^2.

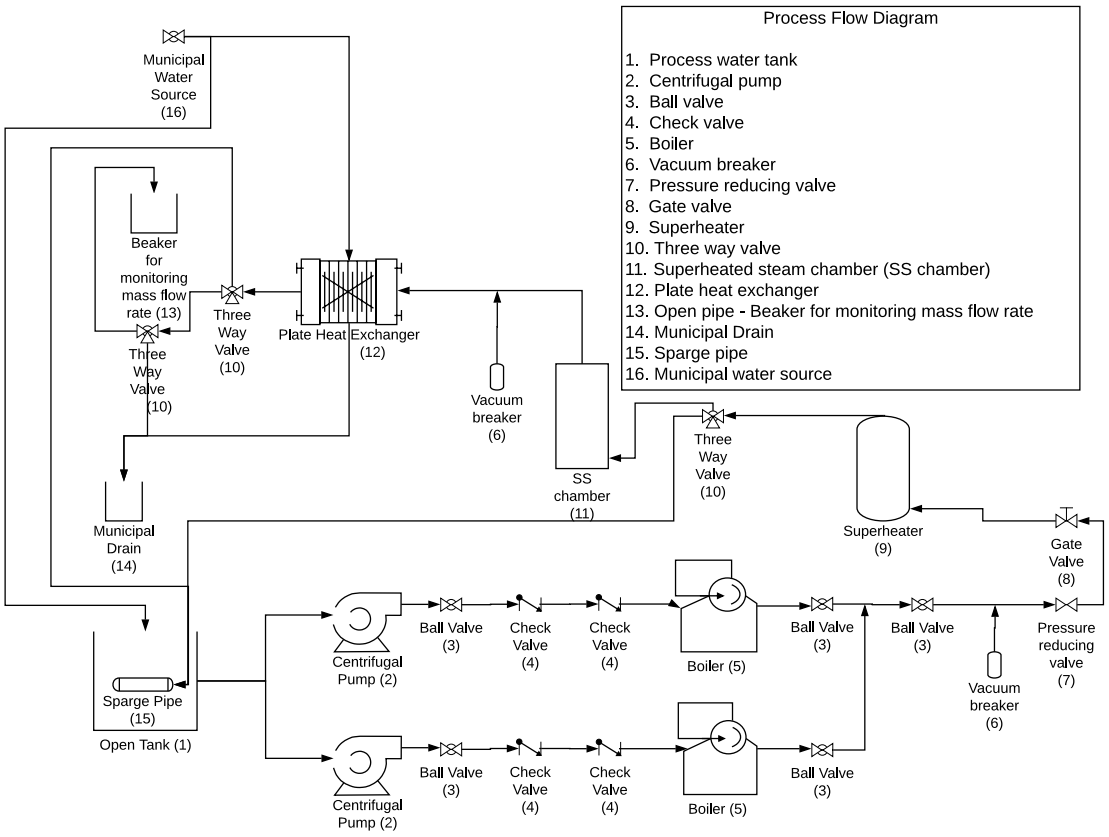


Figure 3.1: Process flow diagram for superheated steam drying.

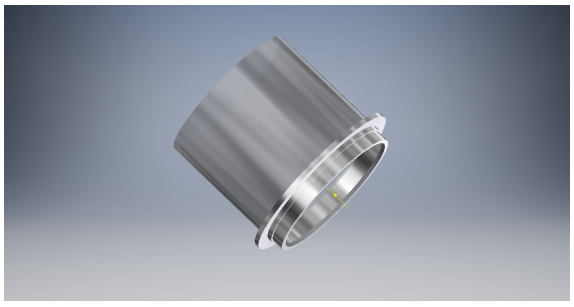


Figure 3.2: A 3D rendering of the aluminum collar and glass cylinder for the container for drying grain using superheated steam (SS). The stainless steel wire mesh sits on the bottom-most lip of the aluminum collar.

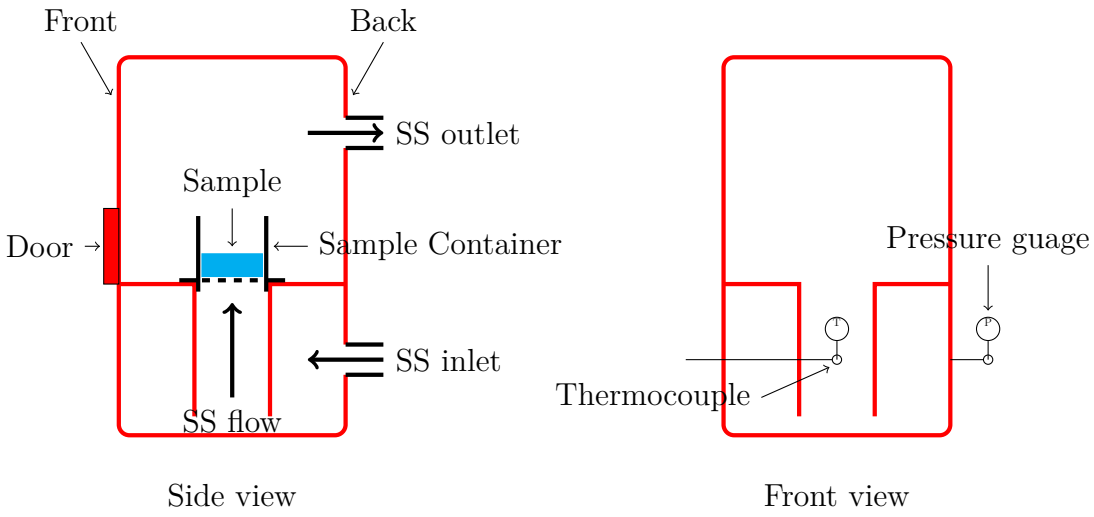


Figure 3.3: Superheated steam (SS) processing chamber cross sections; with sample placement and SS flow (Left); with temperature (thermocouple) and pressure measuring points (Right).

3.3 Moisture content

Moisture content was determined after drying using a moisture tester (Moisture Tester MT-C, C.W. Brabender® Instruments, Inc.; South Hackensack, NJ) following the appropriate standard (AACC Technical 2009b). Moisture content was calculated using Equation 3.2 from AACC Technical (2009a).

$$mc = \frac{\text{loss in moisture (g)}}{\text{wet weight of sample (g)}} \times 100, \tag{3.2}$$

where mc is moisture content (%) in wet basis.

3.4 Steel cutting and size distribution

The dried barley was steel cut on a Kipp Kelly rotary granulator (Two Drum Rotary Granulator, ArrowCrop; Winnipeg, MB) with a №10 wedge and 10/64 hole size.

Unprocessed kernels were retrieved and cut using a №9 wedge and 11/64 hole size. Any uncut kernels were retrieved and weighed. The cut kernels were sieved with a sieve shaker (Ro-Tap® Sieve Shaker RX-29, W.S. Tyler; Mentor, OH) for 5 min using ASTM E-11 Sieves sizes №7 (2.88 mm), №8 (2.36 mm), №12 (1.70 mm), №16 (1.18 mm), №25 (710 µm) and pan. After Ro-tapping the cut barley was divided into two bulgur fractions; coarse bulgur (> 2.36 mm) and fine bulgur ($1.18\,\text{mm} < x < 2.36\,\text{mm}$). This procedure was done in duplicate.

3.5 Effects of drying

After drying, the samples were tested for moisture content, colour, bulk density, 1000 kernel weight, kernel density, total β-glucans content, and presence of tocochromanols (α, β, γ, and δ; tocopherols and tocotrienols). The tests for total β-glucans and tocochromanols were also performed on barley samples that had not undergone any treatments (raw grain). These results were used to determine changes in quality due to processing. Size distribution of the cut kernels, also an effect of drying methodology, was recorded and further testing was conducted on the coarse and fine bulgur portions; colour, cooking time, cooking losses, and water absorption during cooking. Additionally, fine bulgur was tested for soluble β-glucans using a modified assay for soluble β-glucans.

3.5.1 Colour

Spectra of samples in the L* a* b* colour scale were measured using a spectrophotometer (CM-5 Spectrophotometer, Konica Minolta; Tokyo, Japan). The

unit was calibrated before use. The internal software uses four samples to calculate an average and a standard deviation. The output of the unit gives four values; maximum, minimum, mean (average), and a standard deviation. To analyze variance, (ANOVA), a short script was written to find the two intermediate values of spectra. Colour of the whole kernels and the cut kernels, after sieve shaking, for both coarse and fine bulgur portions, were measured after drying

3.5.2 Bulk density

Bulk density (test weight) was determined on treated samples before steel cutting as per instructions in AACC Technical (2009c), with the quart kettle exchanged for a 0.5 L kettle. The bulk density value obtained was doubled and reported as g/L. The process was repeated in triplicate.

3.5.3 1000 Kernel mass

The mass of 1000 kernels also known as thousand kernel weight (1000 KWT) was tested on the whole grain before cutting. Before testing for kernel mass, a sample of about 40 g was inspected, and partial kernels and chaff were removed. The process was repeated in triplicate.

3.5.4 Kernel density

Kernel density of the whole grain was measured, before cutting, using an automatic gas pycnometer with helium as a carrier gas (Ultrapyc 1200e, Quantachrome Instruments; Boynton Beach, FL). The pycnometer was programmed to run three (3) runs per

sample. Three independent samples were used for each treatment. For comparison, raw (not cooked) barley kernels were also tested.

3.5.5 Cooking time

About 300 mL of distilled water was preheated to boiling in a kettle and poured into a 500 mL beaker and placed on a hot plate (Thermo Scientific™, model №SP131325; Waltham, MA) set to 350°C. After gentle boiling was established, 10.0 g of bulgur fraction, coarse or fine, was poured into the beaker. According to the results, established through preliminary trials, testing was initiated several minutes before cooking was anticipated to be completed and thereafter, every minute until the product was deemed to be overcooked. Testing was conducted by removing a small sample portion of the product using a stainless steel sieve. Excess water was removed from the sample by touching the outer edge of the sieve to a paper towel, whereafter, the product was tapped out of the sieve onto a plexiglass plate. A second plexiglass plate was then used to compress the product sample. The product was deemed fully cooked when the white starch core disappeared, and the starch core gently oozed out of the pericarp. To the touch, the product was sticky but not overly adhesive while still maintaining some resilience. Another sample was taken a minute later, at which time the product lost resilience and was subsequently deemed overcooked. The time recorded was when the product was deemed fully cooked (Basman and Yalcin 2011). Cooking time was established in duplicate for each bulgur fraction of each rep obtained from Section 3.4. Optimum cooking time was established using the least square means procedure with bulgur fractions obtained from within a single steel cutting session treated as sub-reps.

3.5.6 Cooking water absorption

About 100 mL of distilled water was preheated to boiling in a kettle and poured into a 500 mL beaker and placed on a hot plate (Thermo Scientific™, model №SP131325; Waltham, MA) set to 350°C. Once gentle boiling was established, 10.0 g of sample was cooked to the optimum time established in Section 3.5.5 (Cooking time). After cooking, the contents of the beaker were poured over a tared steel mesh cloth suspended over a funnel. Excess water and cooking losses were collected in a tared beaker under the funnel. The cooked barley sample was then gently spread across the steel cloth, with a spoon, allowing excess water to drip off, for about one minute (Figure 3.4). The steel cloth was placed on paper towels and slowly rolled so that the entire surface had contact with a dry portion of the paper towels. Contact with the paper towel removed excess water that was held by water tension to the steel cloth. The rolling action took about 10 s (Figure 3.5). Subsequently, the steel mesh and the cooked sample were weighed. Water absorption was calculated as the mass after cooking minus the mass before cooking divided by the mass before cooking as defined (Basman and Yalcin 2011) (Equation 3.3),

$$W_a = \frac{m_c - m_u}{m_u} \times 100, \tag{3.3}$$

where W_a is water absorbed (%), m_c is cooked mass, and m_u is mass of bulgur before cooking.

3.5.7 Cooking losses

The tared beaker with the water used for cooking containing the cooking losses was placed on a hot plate where most of the remaining water was boiled off. The beaker was

then transferred to a drying oven set to 95°C where the remaining water was dried off. The beaker was then placed in a desiccator until cooled and weighed. Cooking losses were calculated as mass lost divided by the original mass before cooking (Equation 3.4) (Basman and Yalcin 2011).

$$C_L = \frac{m_{b+res} - m_b}{m_u} \times 100\%, \tag{3.4}$$

where C_L is the cooking loss, m_{b+res} is the mass of the beaker with cooking losses, and m_b is the mass of the empty beaker.

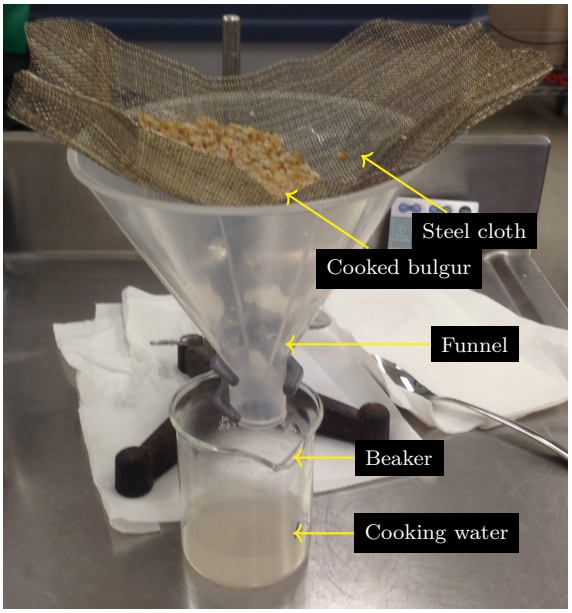


Figure 3.4: Draining water after cooking to determine cooking losses and water absorption.

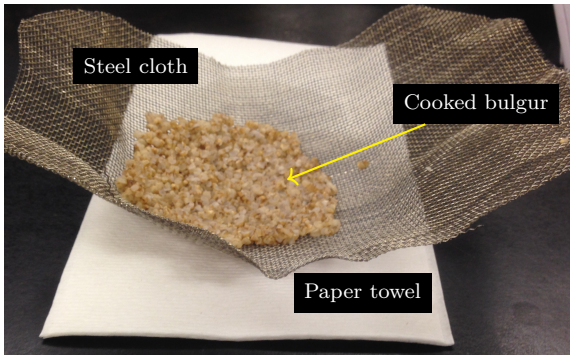


Figure 3.5: Using a paper towel for blotting off excess water held by tension to the steel mesh.

3.5.8 β-glucans

Total β-glucans Total β-glucans content was assayed on whole kernel samples of treated and raw samples, using the Megazyme mixed-linkage β-glucan assay procedure

(McCleary and Codd 1991).

Soluble β-glucans Testing for soluble β-glucans content on the fine bulgur portion was achieved by using the Megazyme procedure with several modifications (McCleary and Codd 1991). About 100 mL of water was brought to a boil on a hot plate in a 250 mL beaker, whereafter, 5.0 g of a fine bulgur sample was added and boiled for 12 min. After boiling, the beaker was placed in a cooling bath with water at room temperature for 2 min. The contents of the beaker were quantitatively transferred to a plastic 250 mL centrifuge bottle with the final mass brought to 130 g using water. A magnetic stir bar was added to the bottle. The sample was incubated at 40°C with the bottle in the horizontal position in an incubator shaker for 60 min (Eppendorf Canada, New Brunswick™ Innova® 40/40R; Canada). The mixture was then filtered using a paper filter (GE Healthcare Life Sciences, Whatman™Fluted (diameter 320 mm); United States). A 2.0 mL sample of the filtered liquid was transferred to a test tube with 2.0 mL of sodium phosphate buffer (20 mM, pH = 6.5). Lichenase, 0.2 mL, was added and the contents were incubated for 60 min at 50°C with vortex mixing every 15 min. After incubation 2.0 mL of sodium acetate was added (200 mM, pH = 4.0) and the mixture was vortexed. An aliquot of 1.5 mL was transferred to an Eppendorf tube and centrifuged at 10k rpm (revolutions per minute) for 10 min (Eppendorf Canada, Eppendorf Centrifuge 5415C; Canada). From each of the centrifuged samples, three aliquots of 0.1 mL each were tested as described in the Megazyme mixed-linkage β-glucan streamline method from step 8 (McCleary and Codd 1991).

3.5.9 Vitamin E - tocopherols and tocotrienols

Tocols were extracted from freshly ground grain samples using saponification under nitrogen according to the method of Nielsen and Hansen (2008), Panfili et al. (2008), Lampi and Piironen (2009), and ISO 9936:2016 (2016), with some modifications. Whole grain samples were ground to 0.5 mm using a rotor mill (Ultra Centrifugal Mill ZM 200, Retsch GmbH, Haan, Germany).

Saponification A 0.25 g sample was subjected to alkaline digestion using 0.5 mL of potassium hydroxide (8.9 M, Sigma 221473) in a screw cap glass tube within a homogenous mixture of 0.1 g ascorbic acid, 5 mL absolute ethanol, and 2 mL water. Alkaline digestion was conducted in a water bath at 70°C for 45 min with vortex mixing every 5 to 10 min. After alkaline digestion, the samples were cooled in an ice bath for 10 min. After cooling, 2.5 mL of water and 2.5 mL of absolute ethanol were added to the tubes.

Extraction Extraction was carried out using 10 mL hexane/ethyl acetate (8:2) (hexane: Fisher AC610070040, ethyl acetate: Sigma 650528 1L) with agitation using a wrist shaker for 10 min (Wrist Action™ Shaker, Model 75, Burrell Scientific; Pittsburgh, PA). After the layers had separated, the upper organic layer was transferred to a 125 mL separatory funnel. Performing the process three times ensured complete extraction. The aqueous layer in the separatory funnel was drained off and discarded. The organic layer was quantitatively transferred to a 50 mL glass tube and evaporated to dryness under a stream of nitrogen. Residual water was removed by adding 2 mL of absolute ethanol and evaporating to dryness. The lipid residues were dissolved

in Hexane (Sigma 650552) and quantitatively transferred to 5 mL volumetric flasks. Samples were stored at 20°C if not analyzed immediately.

High-Performance Liquid Chromatography (HPLC) Chromatographic separation of the 8 chemical forms of vitamin E ($\alpha, \beta, \gamma, \delta$ tocopherol and $\alpha, \beta, \gamma, \delta$ tocotrienol) was achieved using Kromasil KR60-5-Diol column (250 mm x 4.6 mm, particle size 5 µm, Supelco) normal phase column protected with a Supelcosil LC-Diol Supelcoguard guard columns (20 µm x 4 mm, particle size 5 µm, Supelco). Samples were filtered through a 0.455 µm nylon filter into amber HPLC vials. The mobile phase was hexane/ethyl acetate/acetic acid (94.6:3.6:1.8), with a flow rate of 1.0 mL/min (Waters ® 2695 Separations Module, Waters; Mississauga, ON). Between injections, the column was conditioned with 10 % isopropanol in hexane. Fluorometric detection (Waters ® 2475 Fluorescence Detector, Mississauga, ON) of all peaks was performed at an excitation wavelength of 292 nm and an emission wavelength of 325 nm. Pure tocopherol standards were purchased from Sigma-Aldrich. Tocotrienol standards are not commercially available, so the calibration curves prepared for the four tocopherol standards were used to quantify the respective tocopherol and tocotrienol vitamer. The saponification extraction procedure was carried out in duplicate, and all results are reported on a dry mass basis.

3.6 Software and data analysis

Data was stored in Microsoft Excel spreadsheets. Statistical analysis and graphs were done using Python 3.5.2 (Python Software Foundation 2016) with the following libraries: SciPy (Jones et al. 2018), Pandas 0.23.0 (McKinney 2010), Numpy 1.13.1

(Travis E 2006), Matplotlib 1.5.1 (Hunter 2007), and Statsmodels 0.8.0 (Seabold and Perktold 2010).

4. *Analysis*

Two individual ANOVA tests were conducted on the results with single explanatory variables set first for variety and then for treatment, with $\alpha < 0.05$. If one of the explanatory variables returned a significant difference, then a Tukey's HSD pairwise test was conducted for that variable, otherwise the ANOVA test was used. Additionally, an ANOVA was conducted on drying treatments after isolation by variety. For tests involving different sizes of bulgur (coarse and fine), the outcomes were analyzed for the significance of the variation in bulgur size before and after separating by variety.

To establish a model for SS treatments with respect to temperatures an ordinary least squares (OLS) model was fit with temperature as the explanatory variable (x =110, 120, and 130°C). A linear model with one first-order variable for line slope and one first order variable as an intercept was developed. ($y = \beta_0 + \beta_1 T_{SS} + \varepsilon$, where y is the value obtained, β_0 is the intercept, β_1 is the slope, T_{SS} is the temperature setting for SS, and ε is the error value; excluding ε returns the predicted y value.) For a model to be considered significant, the α p-value for the F-test was set to 0.05. For a significant model to be considered a good fit a min value for the adjusted R^2 (aR^2) value was set to > 0.8. The formula for aR^2 is $aR^2 = R^2 - \frac{(k-1)}{(n-k)}(1 - R^2)$, where R^2 is the R squared value, n is the number of points in the data sample, and k is the number of parameters. For OLS regression models the aR^2 value was rounded to 2

significant digits and assessed. Models with aR^2 values less than 0.75 were generally considered to be non-explanatory.

For ANOVA results, the p-value was rounded to one significant digit but where values were $p < 10^{-4}$ the notation $p \ll 0.05$ was applied.

Deviations and clarifications from the analysis method described above, for individual tests, are outlined in Sections 4.1 to 4.8.

4.1 Moisture content

The ending targeted moisture content for all drying treatments was 9 % (wet basis); however, the targeted moisture content was not reached for several of the samples. An F-test showed that the differences in end moisture contents were significant. A pairwise test was conducted after sorting according to unique groupings of variety and treatment as this test was conducted to evaluate the accuracy of the work as opposed to treatment methods or differences in varieties. To determine if the variation in values for of the final moisture contents significantly influenced the results OLS models were constructed with moisture content values as explanatory and the test results as dependent values. An OLS model for each variety by bulgur size, if applicable, was calculated. The p-values for the F-tests of the regression models based on moisture content as the explanatory variable were compared to the p-values of ANOVA based on the treatments for the explanatory variable to determine which had a more significant influence.

4.2 Porosity

Although porosity was not tested directly, values with linear relationships to actual porosity can be obtained by using Equation 4.1 with the dry mass values of the bulk and kernel densities. The mean values for both bulk and kernel densities were used for calculating porosity. Therefore, the resulting values are not accompanied by SD values, and an ANOVA could not be done on the results. The porosity values calculated include pores in the kernel as well as void spaces in the measuring kettle. The assumption is that the kernels maintain their geometric shapes regardless of drying treatment and that the air to kernel ratio in the bulk density test is therefore similar for all treatments. With the assumption of air to kernel volume ratios remaining constant, the calculated values for porosity are assumed to have a linear relationship to the actual porosity of the kernels.

$$\phi = 1 - \frac{\rho_b}{\rho_k}, \tag{4.1}$$

where ϕ is porosity, ρ_b is bulk density, and ρ_k is kernel density.

4.3 Size distribution

A modulus of fineness (MF) was calculated for the particle sizes. The method for calculating MF is generally to use sieve sizes where each sieve has twice the aperture size of the one beneath it. The smallest aperture size, 0.15 mm, receives a multiplication factor of 1 and each sieve size larger receiving a multiplication factor of the previous sieve size plus 1. The multiplication factor can be mathematically determined using Equation 4.2. For this study, the smallest sieve size was 710 µm which was designated a

multiplication factor of 1.00. The value for fineness factor is calculated using Equation 4.3. The sum of the fineness factors is the MF for that rep of Ro-tapping (Equation 4.4). Table 4.1 contains the resulting multiplication factors for the sieve sizes and bulgur size designations for this study.

$$mf_i = \log_2 \frac{s_i}{s_{\min}} + 1, \tag{4.2}$$

where mf is the multiplication factor corresponding to the ith sieve, s is the aperture size of the ith sieve, and $s_{\min}$ is the min aperture size.

$$ff_i = mf_i \frac{m}{tm}, \tag{4.3}$$

where ff is the i^{th} fineness factor, m is the mass of material remaining of i^{th} sieve, and tm is the total mass of material Ro-tapped.

$$MF = \sum_i ff_i, \tag{4.4}$$

where MF is the modulus of fineness.

4.4 Colour

The difference between two measured colours in the L*, a*, b* colour scale can be approximated using an algorithm which produces a value termed Delta E (ΔE). The current and most precise Delta E algorithm is subscripted 00; Delta E_{00} (ΔE_{00}) (Sharma et al. 2004). Delta E_{00} analysis has the advantage of measuring colour differences between two values incorporating all three values in the L*, a*, b* colour scale. The average values for dried barley and bulgur (coarse and fine) were compared

Table 4.1: Sieve size multiplication factors for calculating fineness factor and modulus of fineness. Bulgur sizes for corresponding sieve size.

Sieve №	Sieve aperture size [mm]	Multiplication factor	Bulgur size
7	2.88	3.02	coarse
8	2.36	2.73	coarse
12	1.70	2.26	fine
16	1.18	1.73	fine
25	0.710	1.00	residue
pan		0.00	residue

Multiplication factor is calculated using Equation 4.2.

to a pure white colour L* = 100, a* = b* = 0 using the ΔE_{00} algorithm. After obtaining these values, they were compared to the L* values. It was found that when summed together (L* + ΔE_{00}) the difference between the max value and the min value was 1.1% which is negligible. Based on the insignificant difference between these sums it was decided to do ANOVA and regression analysis on the L* values.

4.5 Bulk density

The values for bulk density were analyzed for correlation to final moisture content based on the dry mass basis. The ANOVA test and regression models were conducted on bulk density values for dry mass basis. For confirmation that the bulk density values were a result of the differences in drying techniques and not correlated to the final moisture contents, a statistical analysis was also performed on the bulk density values on a wet mass basis.

4.6 1000 kernel mass

The mass of 1000 kernels also known as thousand kernel weight (1000 KWT) was tested on the whole grain before steel cutting. The 1000 KWT is reported on a dry mass basis.

4.7 Kernel density

Assuming that the effects of moisture are negligible on the volume of the starch, proteins, and other components, such that moisture is restricted to the capillaries the kernel density with 0 % moisture can be calculated according to Equation 4.5 (Fang and Campbell 2000). Results were reported as kernel density for dry mass after applying Equation 4.5.

$$\rho_0 = \frac{1 - mc}{\frac{1}{\rho_k} + \frac{mc}{\rho_w}}, \tag{4.5}$$

where ρ_0 is the kernel density with 0% moisture, ρ_k is the measured kernel density, ρ_w is the density of water (assumed 1 g/cm^3), and mc is the moistue content in decimal (wet basis).

4.8 Vitamin E

The values for tocochromanol content, w/w, were sorted and separated by variety and tail configuration before conducting an ANOVA. These values were then divided by those obtained for raw barley to determine the % retention for each variety by drying

treatment. The value for each tocochromanol was divided by the sum of the eight tocochromanols to obtain the proportion (%) of each tocochromanol in the barley according to variety and drying treatment.

5. *Results*

5.1 Moisture content

Table 5.1 lists the results moisture content values at the completion of the drying experiments using three techniques; hot air, microwave, and superheated steam at temperatures of 110, 120, and 130°C.

Table 5.1: Moisture content at the completion of the drying experiments. Barley was dried using three drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Variety	**Drying treatment**	**Moisture content (wet basis) % ± SD**
CDC Hilose	HA	9.72 ± 0.04^{g}
	MW	11.86 ± 0.07^{e}
	SS 110°C	14.70 ± 0.02^{a}
	SS 120°C	11.10 ± 0.04^{f}
	SS 130°C	13.68 ± 0.11^{c}
CDC Marlina	HA	9.75 ± 0.04^{g}
	MW	11.11 ± 0.05^{f}
	SS 110°C	14.10 ± 0.00^{b}
	SS 120°C	11.98 ± 0.00^{e}
	SS 130°C	13.42 ± 0.02^{d}

[a-g] Values with different superscripts are significantly different (Tukey's HSD $p < 0.05$).

5.2 Porosity

Hot air dried barley had the lowest porosity values. Generally, an increase in superheated steam temperature resulted in higher porosity values. Although an ANOVA was not conducted, it appears that the differences in porosity values between SS 110 and SS 120 treatments are negligible and that the higher porosity value of SS 130 dried barley demonstrates the effects of increased temperature. Microwave dried barley had porosity values close to those for SS 110 and SS 120 (Table 5.2).

Table 5.2: Estimations of (relative) kernel porosity values with assumed linear relationships to actual porosity values. Based on calculations using dry mass bulk and dry mass kernel density values. (Equation 4.1)

Variety	Drying treatment	Kernel porosity
CDC Hilose	HA	0.52
	MW	0.59
	SS 110°C	0.58
	SS 120°C	0.57
	SS 130°C	0.63
CDC Marlina	HA	0.53
	MW	0.57
	SS 110°C	0.60
	SS 120°C	0.59
	SS 130°C	0.64

Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

5.3 Size distribution

The moisture content of the final product was found to be an unreliable indicator of modulus of fineness (MF). When both varieties were included in the model the regression values were ($p = 0.007$, $aR^2 = 0.30$). Although, after separating by variety significant differences were not found ($p = 0.1$, $aR^2 = 0.22$) and ($p = 0.05$, $aR^2 = 0.33$) for CDC Hilose and CDC Marlina, respectively. Porosity, however, was a good indication for MF. For CDC Hilose $MF = -1.61P + 3.32$ ($p \ll 0.05$, $aR^2 = 0.91$); where MF is modulus of fineness and P is porosity. For CDC Marlina $MF = -2.22P + 3.69$ ($p = 0.0002$, $aR^2 = 0.82$) (Figure 5.1).

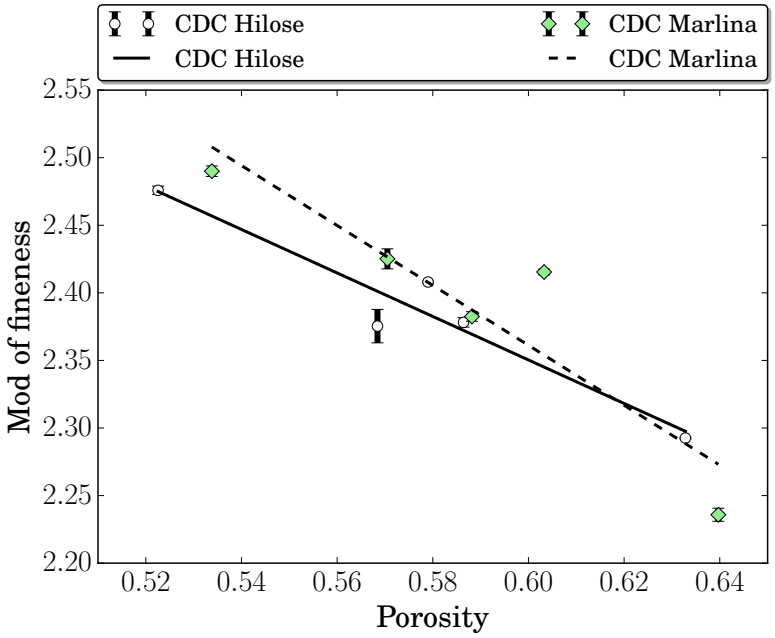


Figure 5.1: The modulus of fineness values for dried barley, for CDC Hilose and CDC Marlina. Porosity values were fit as the independent variables and modulus of fineness values as the dependent variables. Points are the means of the values and error bars are standard error values.

The variety of barley was not found to have a significant influence on the MF

values ($p = 0.9$). Drying treatment was, however, found to be a significant factor ($p \ll 0.05$) (Table 5.3; Figure 5.2).

As higher temperatures of SS are expected to produce a more brittle product a regression model was used to correlate MF to processing temperature. When fitting a linear model for SS temperatures for either variety a good fit was obtained for MF. CDC Hilose: $MF = (-5.77 \times 10^{-3}/°\text{C})T_{SS} + 3.05$ ($p = 0.002$, $\text{aR}^2 = 0.90$); where MF is the modulus of fineness and T_{SS} the temperature of the superheated steam from 110 to 130°C. For CDC Marlina $MF = (-8.98 \times 10^{-3}/°\text{C})T_{SS}/ + 3.42$ ($p = 0.006$, $\text{aR}^2 = 0.85$) (Figure 5.3).

Table 5.3: Modulus of fineness values for steel cut barley.

Variety	Drying treatment	Modulus of fineness
CDC Hilose	HA	$2.48 \pm 0.00^{\text{a;A}}$
	MW	$2.38 \pm 0.00^{\text{b;C,D}}$
	SS 110°C	$2.41 \pm 0.00^{\text{b;B,C}}$
	SS 120°C	$2.38 \pm 0.02^{\text{b;D}}$
	SS 130°C	$2.29 \pm 0.00^{\text{c;E}}$
CDC Marlina	HA	$2.49 \pm 0.01^{\text{1;A}}$
	MW	$2.43 \pm 0.01^{\text{2;B}}$
	SS 110°C	$2.42 \pm 0.00^{\text{2;B}}$
	SS 120°C	$2.38 \pm 0.01^{\text{3;C,D}}$
	SS 130°C	$2.24 \pm 0.01^{\text{4;F}}$

$^{\text{a-c}}$ for CDC Hilose (above dashed horizontal line), $^{\text{1-4}}$ for CDC Marlina (below dashed horizontal line), and $^{\text{A-F}}$ for both varieties; values with different superscripts are significantly different (Tukey's HSD $p < 0.05$).
Standard deviations of 0.00 are not zero but < 0.00 after rounding.
Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

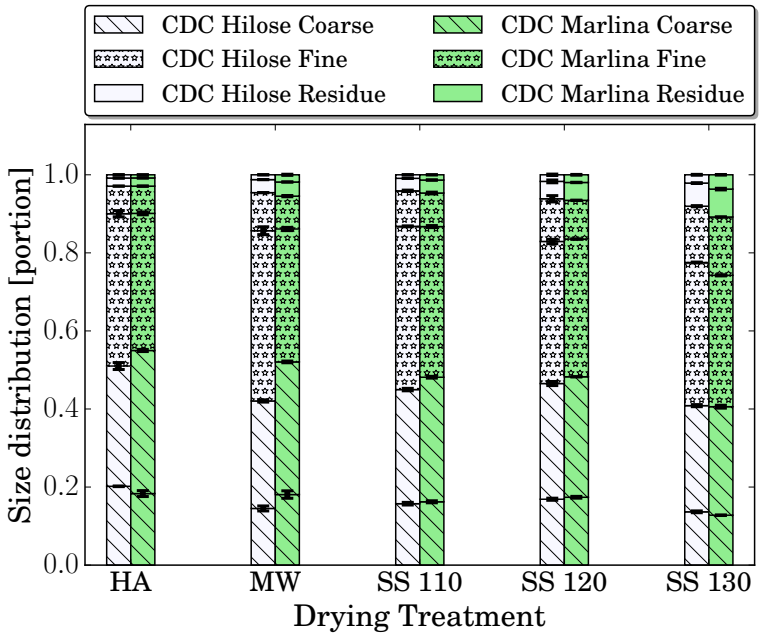


Figure 5.2: Size Distribution, by mass. Drying treatments; hot air (HA), microwave (MW), and superheated steam (SS) at temperatures 110, 120, and 130°C. Error bars are standard deviations. Sieve sizes are separated by black horizontal lines (bottom to top) 7, 8, 12, 16, 25, and pan.

5.4 Colour

Table A.4 lists the values for L*, a*, b*, ΔE_{00} values when compared to white (L* = 100, a* = b* = 0), and the sums of L* and the ΔE_{00} values.

Regression tests showed no correlation between moisture content and L* values ($p > 0.05$ and aR^2 approx. 0.0).

Without separating the L* values by bulgur size or by treatment, an ANOVA gave no significant difference between varieties ($p = 0.4$). However, by cut and by treatment significant differences were found ($p \ll 0.05$). Fine bulgur was significantly lighter than coarse bulgur, which was significantly lighter than whole barley. Increasing the temperature for superheated steam drying treatments generally resulted in a significant

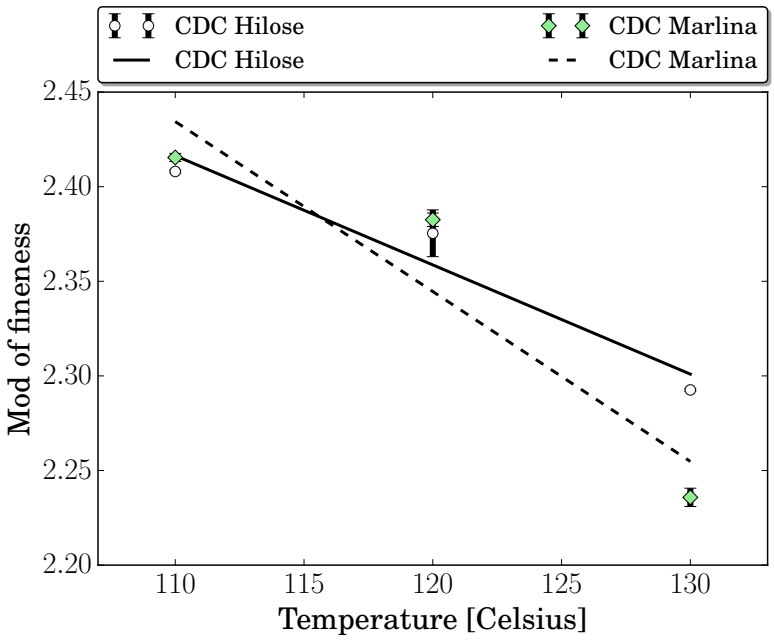


Figure 5.3: The modulus of fineness values for dried barley, for CDC Hilose and CDC Marlina. Temperature values were fit as the independent variables and modulus of fineness values as the dependent variables. Points are the means of the values and error bars are standard error values.

increase in L* values (Tables A.1, A.2, A.3, and Figure 5.5).

A linear relationship between L* values and temperature values for SS treatments with least squares regression returned low p values (<0.05) and high aR^2 values (>0.73). The regression model for CDC Hilose coarse bulgur was $L = (0.22/°C)T_{SS} + 15.83$ ($p = 0.0001$, $aR^2 = 0.98$); where L is the L* value from colour analysis (no units) and T_{SS} is the temperature of the superheated steam from 110 to 130°C. For CDC Hilose fine bulgur the relationship was $L = (0.18/°C)T_{SS} + 23.22$ ($p = 0.02$, $aR^2 = 0.73$), for CDC Marlina coarse bulgur $L = (0.28/°C)T_{SS} + 8.66$ ($p = 0.0005$, $aR^2 = 0.95$), for CDC Marlina fine bulgur $L = (0.32/°C)T_{SS} + 7.60$ ($p = 0.002$, $aR^2 = 0.90$), for CDC Hilose dried grain $L = (0.20/°C)T_{SS} + 14.93$ ($p \ll 0.05$, $aR^2 = 0.97$), and for CDC Marlina dried grain $L = (0.29/°C)T_{SS} + 5.22$ ($p \ll 0.05$, $aR^2 = 0.92$) (Figure 5.4).

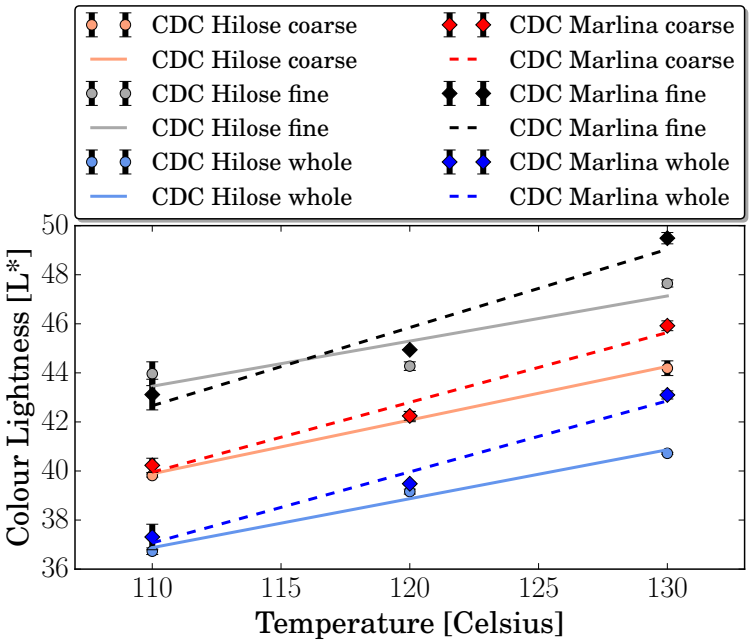


Figure 5.4: The L* values for bulgur (coarse and fine) and dried barley, for CDC Hilose and CDC Marlina. Superheated steam (SS) at temperatures 110, 120, and 130°C was fit as the independent variable and L* values as dependent values. Points are the means of the values and error bars are standard error values.

5.5 Bulk density

An OLS regression model correlating bulk density (wet basis) to final moisture content was not explanatory. The aR^2 values were -0.02 and 0.09, while the p-values for F-tests returned 0.41 and 0.33 for CDC Hilose and CDC Marlina, respectively. Whereas reporting bulk density on a dry mass basis the aR^2 values were 0.18 and 0.26, while the p-values for F-tests returned 0.26 and 0.22 for CDC Hilose and CDC Marlina, respectively. It is, therefore, reasonable to conclude that the variation in moisture content was not a significant influencing factor for bulk density. F-tests results for bulk density, dry mass, revealed that variety was not significant ($p = 0.49$). The p-value for ANOVA for drying treatments was $\ll 0.05$. Table A.5 contains the values for bulk

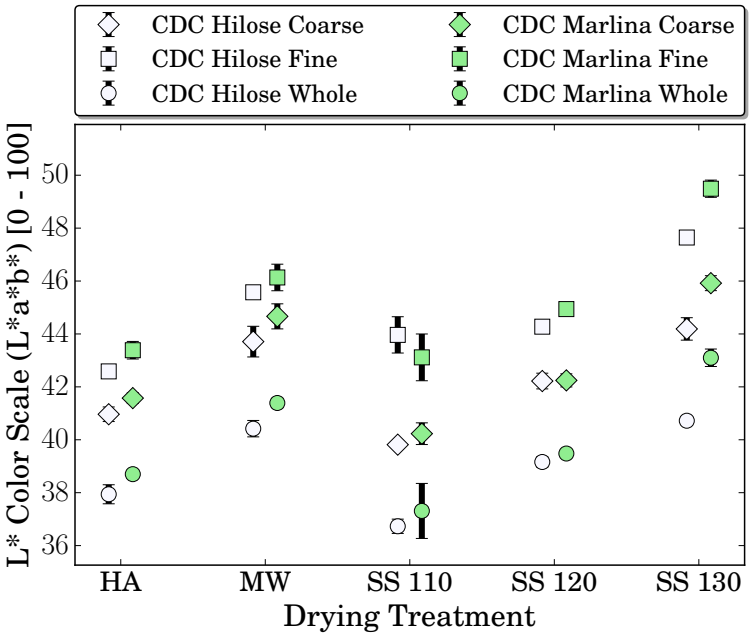


Figure 5.5: The L* values for bulgur (coarse and fine) and dried barley, for CDC Hilose and CDC Marlina. Drying treatments; hot air (HA), microwave (MW), and superheated steam (SS) at temperatures 110, 120, and 130°C. Error bars are one standard deviation.

density both as measured and also the calculated values for bulk density on a dry mass basis. Figure 5.6 displays the values for bulk density on a dry mass basis.

It was found that the effect of increasing the temperature for the SS treatments was a significant decrease in bulk density values. For both varieties, the relationship between temperature and bulk density, dry mass basis, fit well to a linear equation. For CDC Hilose the regression model was $BD = (-5.32\,(\mathrm{g/L})/^{\circ}\mathrm{C})T_{SS} + 1204\,\mathrm{g/L}$ ($p \ll 0.05$, $\mathrm{aR}^2 = 0.91$); where BD is bulk density, dry mass basis, in g/L, and T_{SS} is the temperature of the superheated steam from 110 to 130°C. For CDC Marlina the regression model was $BD = (-5.92\,(\mathrm{g/L})/^{\circ}\mathrm{C})T_{SS} + 1258\,\mathrm{g/L}$ ($p \ll 0.05$, $\mathrm{aR}^2 = 0.93$) (Figure 5.7).

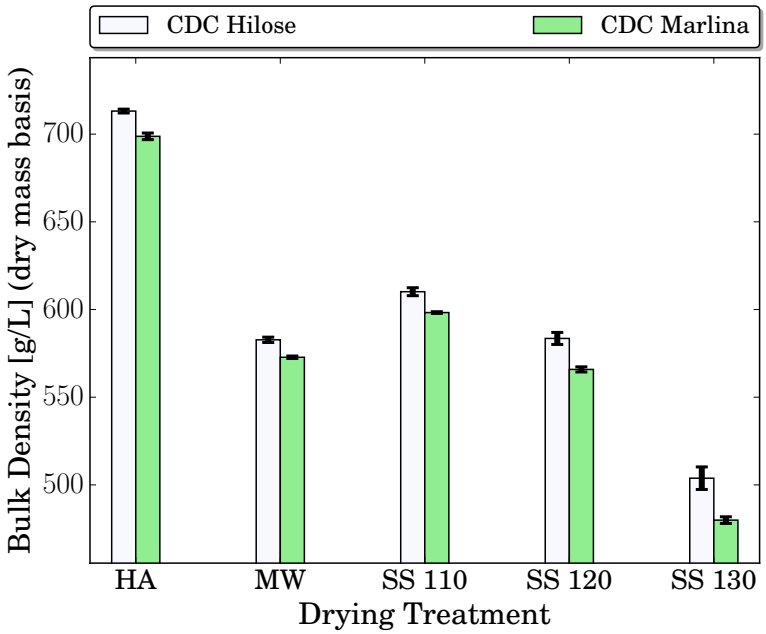


Figure 5.6: Comparison of bulk density values ,dry mass. Drying treatments; hot air (HA), microwave (MW), and superheated steam (SS) at temperatures 110, 120, and 130°C. Error bars are standard deviations.

5.6 1000 kernel mass

Linear regression analysis found no relationships between the kernel mass values and the moisture content values obtained at the completion of the drying experiments. For CDC Hilose the p-value and aR^2 value were 0.4 and 0.014, respectively and for CDC Marlina, also respectively, they were 0.05 and 0.27.

Variety of grain was found to significantly influence results ($p \ll 0.05$) values of kernel mass for CDC Hilose were significantly higher than those for CDC Marlina, whereas, no significant difference was found between treatments ($p = 0.64$). Drying treatments were not significantly different for CDC Hilose $p = 0.5$ or CDC Marlina $p = 0.06$ (Table 5.4).

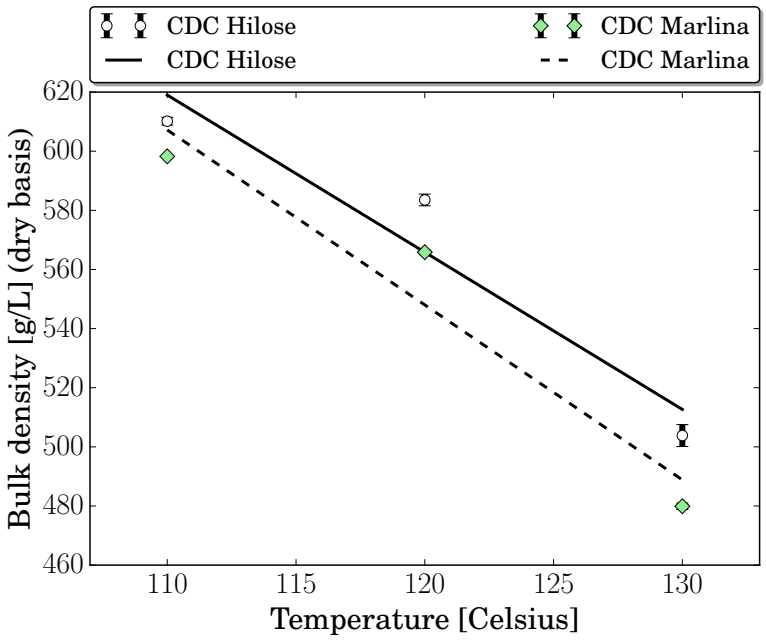


Figure 5.7: The dry mass, bulk density values for dried barley, for CDC Hilose and CDC Marlina. Superheated steam (SS) at temperatures 110, 120, and 130°C was fit as the independent variable and bulk density values as dependent variables. Points are the means of the values and error bars are standard error values.

5.7 Kernel density

Variations in kernel density (dry basis) were not found to have any correlation to final moisture content, with results separated by variety, the p-values were 0.44 and 0.84 and the $aR^2 < 0$, for CDC Hilose and CDC Marlina, respectively. Variety was not an influencing factor for kernel density (dry basis) $p = 0.8$, however, treatment was $p \ll 0.05$ (Figure 5.8). All treatments resulted in a lower kernel density than that of untreated grains with the two higher temperatures of superheated steam and microwave treatments (MW, SS 120, and SS 130) having a more pronounced effect in this regard than hot air drying or superheated steam at 110°C (Table A.6.)

A linear regression model for CDC Marlina relating the decline in kernel density to

Table 5.4: Thousand kernel mass, dry mass, after drying grain, based on whole kernels.

Variety	Drying treatment	1000 kernels g ± SD
CDC Hilose	HA	$32.73 \pm 0.32^{A,B}$
	MW	$32.79 \pm 0.25^{A,B}$
	SS 110°C	$32.56 \pm 0.25^{A,B}$
	SS 120°C	33.21 ± 0.82^{A}
	SS 130°C	$32.86 \pm 0.13^{A,B}$
CDC Marlina	HA	$31.86 \pm 0.26^{B,C}$
	MW	$31.78 \pm 0.31^{B,C}$
	SS 110°C	31.41 ± 0.13^{C}
	SS 120°C	$32.17 \pm 0.44^{A,B,C}$
	SS 130°C	31.37 ± 0.22^{C}

[A-C] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by row.
Abbreviations for drying treatments: MW - microwave dried, SS - superheated steam dried, HA - hot air dried.
Broken kernels and chaff were removed before weighing.

increased SS temperature fit well; $KD = (-8.80 \times 10^{-3}\,\mathrm{g/(cm^3\,°C)})T_{SS} + 2.46\,\mathrm{g/cm^3}$ ($p \ll 0.05$, $\mathrm{aR^2} = 0.89$); where KD is kernel density, dry weight, in $\mathrm{g/cm^3}$ and T_{SS} is the temperature of the superheated steam from 110 to 130°C (Figure 5.9). CDC Hilose did not fit a regression model relating kernel density to SS temperature. For CDC Hilose the density from the SS treatment of 110°C was significantly higher than that for the SS treatment of 120°C, however, after that, an increase in temperature did not produce any significant change in kernel density.

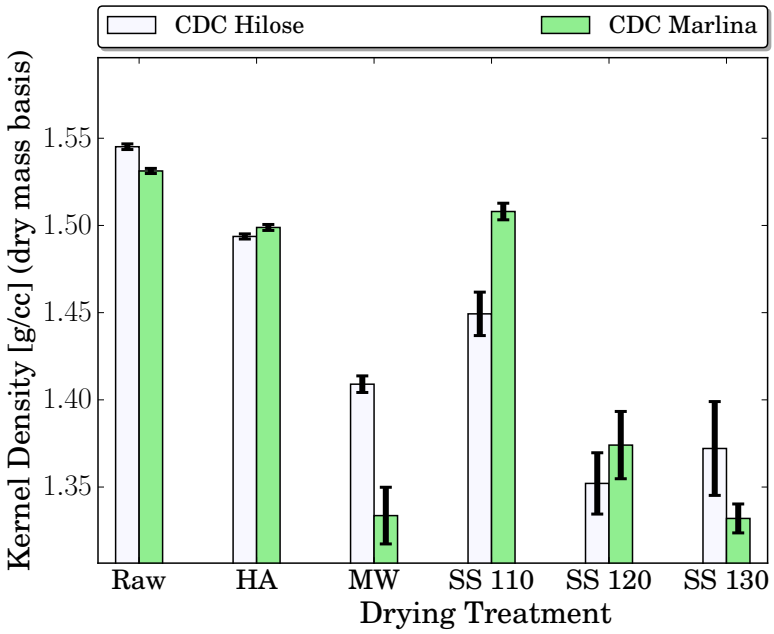


Figure 5.8: Comparison of kernel density, dry mass. Drying treatments; hot air (HA), microwave (MW), and superheated steam (SS) at temperatures 110, 120, and 130°C. Error bars are standard deviations. The dry mass kernel density of the raw grains are included for comparison.

5.8 Cooking time

Cooking time for CDC Marlina was significantly less than for CDC Hilose ($p \ll 0.05$). The coarse bulgur required significantly more time to cook than the fine bulgur ($p \ll 0.05$) (Figure 5.10).

CDC Hilose coarse bulgur For CDC Hilose coarse bulgur, differences in moisture content were significantly related to cooking time ($p = 0.02$, $\mathrm{aR}^2 = 0.48$). Higher moisture content was correlated with less cooking time. Hot air dried bulgur required significantly more time to cook than bulgur made employing the other drying treatments, but no significant differences were found between the other methods

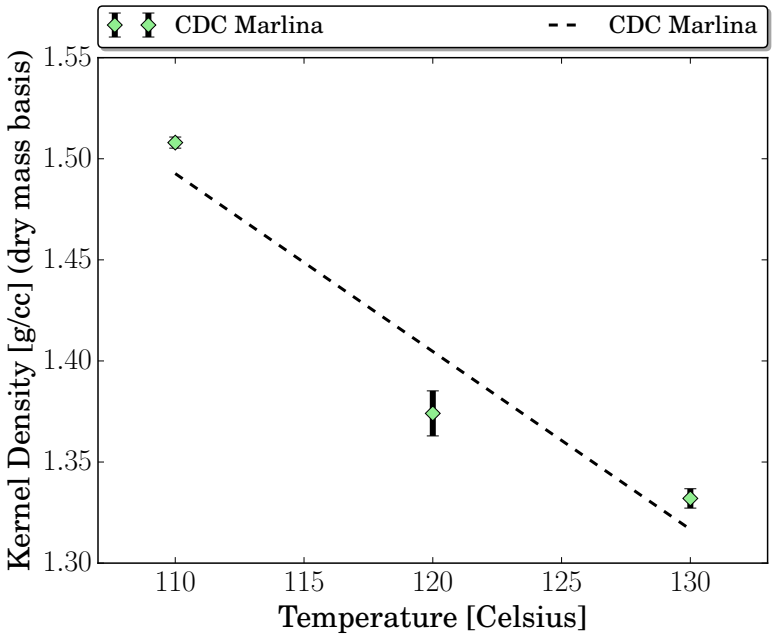


Figure 5.9: The dry mass, kernel density values for dried barley, for CDC Hilose and CDC Marlina. Superheated steam (SS) at temperatures 110, 120, and 130°C was fit as the independent variable and kernel density values as dependent variables. Points are the means of the values and error bars are standard error values.

of drying. A correlation with a higher aR^2 value and a lower p-value was found by using porosity to explain variation in cooking time ($p = 0.005$, $aR^2 = 0.61$). Results from an ANOVA on the cooking times, irrespective of moisture content or porosity, returned a lower p-value ($p = 0.001$) (Table A.7).

CDC Hilose fine bulgur For CDC Hilose fine bulgur, a correlation between higher moisture content and less cooking time was also found ($p = 0.002$, $aR^2 = 0.67$). A regression test using porosity returned a better model relating higher porosity to less cooking time ($p = 0.001$, $aR^2 = 0.72$). An ANOVA, with no regard for moisture content or porosity, returned a p-value similar to that for the moisture content regression model ($p = 0.002$) (Table A.7).

CDC Marlina coarse bulgur CDC Marlina coarse bulgur cooking time was found to be significantly correlated to moisture content ($p \ll 0.05$,$aR^2 = 0.85$) and porosity ($p \ll 0.05$, $aR^2 = 0.88$) with higher values of moisture content or porosity coinciding with less cooking time. When the model was fit for treatment, irrespective of moisture content, the p-value was similar ($p \ll 0.05$) (Table A.8).

CDC Marlina fine bulgur The regression model fitting CDC Marlina fine bulgur to moisture content fit better than the model for CDC Marlina coarse bulgur ($p = 0.001$, $aR^2 = 0.71$), the model for porosity was a still better fit ($p = 0.0001$, $aR^2 = 0.84$). Both higher moisture content and higher porosity corresponded to less cooking time. The significance of treatment, without regard for moisture content or porosity, was more pronounced ($p = 0.0004$) (Table A.8).

5.9 Cooking water absorption

The results of bulgur water absorption during cooking were not affected by differences in moisture content values before cooking ($p > 0.05$). The regression models for water absorption returned aR^2 values less than zero with the sole exception for CDC Hilose coarse bulgur $aR^2 = 0.30$, which was attributed to the SS 110 treatment. Removing the SS 110 treatment values from the CDC Hilose coarse bulgur regression model returned a aR^2 value of less than zero.

Variety was not a significant factor for water absorption ($p > 0.05$). Fine bulgur absorbed significantly more water than coarse bulgur ($p \ll 0.05$). Further analysis was done after splitting the results by variety and bulgur size (Figure 5.11). Results, including the pair-wise comparisons are included in Appendix A Tables A.9 and A.10

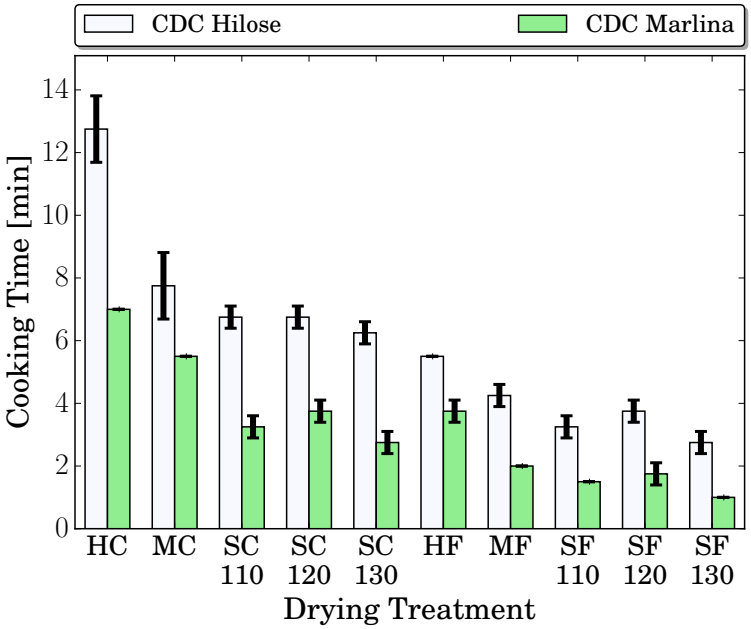


Figure 5.10: Cooking time [min] for bulgur. Error bars are standard deviations. Abbreviations: Drying treatments are denoted by the first letter under the corresponding bar: H - hot air dried, M - microwave dried, S - superheated steam dried. Bulgur size is indicated by the second letter C - coarse bulgur, F - fine bulgur. The numbers 110, 120, and 130 are temperatures in °C for superheated steam.

for CDC Hilose and CDC Marlina, respectively.

Higher temperatures of SS increased water absorption rates at predictable linear rate. CDC Hilose coarse bulgur saw significant differences from 110 to 120°C and only an insignificant rise in absorption to 130°C. The linear model for CDC Hilose coarse bulgur was $A = (0.95/°C)T_{SS} - 19.70$ ($p = 0.003$, $aR^2 = 0.88$); where A is absorption (% w/w) and T_{SS} is the temperature of the superheated steam from 110 to 130°C. CDC Hilose fine bulgur had a linear model of $A = (1.34/°C)T_{SS} - 39.85$ ($p = 0.0003$, $aR^2 = 0.97$). For CDC Marlina coarse bulgur the model was $A = (1.66/°C)T_{SS} - 111.40$ ($p \ll 0.05$, $aR^2 = 0.98$). CDC Marlina fine bulgur absorption rates increased insignificantly from 110 to 120°C but significantly from 120 to 130°C.

The linear model for CDC Marlina fine bulgur was $A = (2.31/°C)T_{SS} - 141.58$ ($p = 0.004$, $aR^2 = 0.87$). The rate of increasing absorption per unit rise in temperature was higher for fine bulgur than for coarse bulgur and also higher for CDC Marlina than for CDC Hilose (Figure 5.12).

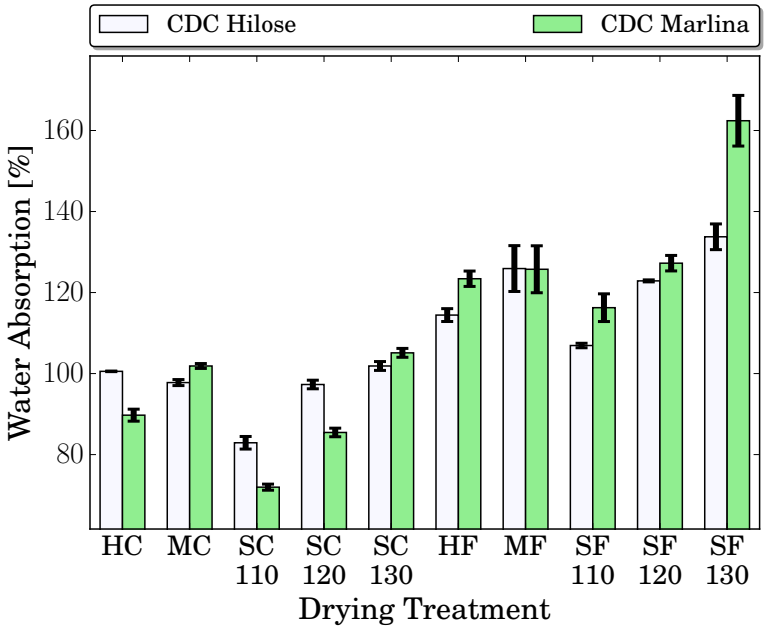


Figure 5.11: Water absorption while cooking (% w/w) for bulgur. Error bars are standard deviation. Abbreviations: Drying treatments are denoted by the first letter under the corresponding bar: H - hot air dried, M - microwave dried, S - superheated steam dried. Bulgur size is indicated by the second letter C - coarse bulgur, F - fine bulgur. The numbers 110, 120, and 130 are temperatures in °C for superheated steam.

5.10 Cooking losses

Analysis of regression by the variety and bulgur size revealed that discrepancies in final moisture content were not an influencing factor in differences in cooking losses ($p > 0.05$, aR^2 values approx 0). The only regression model that returned a higher aR^2

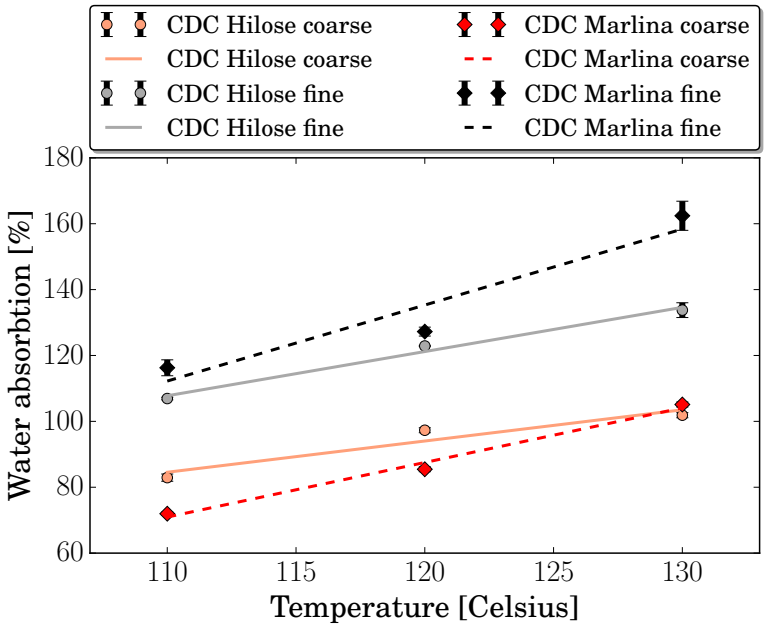


Figure 5.12: The values for bulgur (coarse and fine) cooking absorption values, for CDC Hilose and CDC Marlina. Superheated steam (SS) at temperatures 110, 120, and 130°C was fit as the independent variable and cooking absorption values as dependent variables. Points are the means of the values and error bars are standard error values.

value was for CDC Marlina fine bulgur whose model aR^2 value was 0.21 which was higher than the other models due to hot air dried bulgur, and removing this treatment from the model returned an aR^2 value of less than 0.

CDC Hilose had significantly more cooking losses than CDC Marlina ($p \ll 0.05$), and fine bulgur more than coarse bulgur ($p < 0.05$). The difference between coarse and fine bulgur cooking losses was more pronounced in CDC Hilose ($p \ll 0.05$) than in CDC Marlina ($p = 0.002$) (Figure 5.13).

Regression models fitting SS temperatures to cooking losses fit well for CDC Hilose bulgur but not for CDC Marlina bulgur as the differences in temperature for CDC Marlina bulgur did not produce significant differences in values of cooking losses (Table A.12). Cooking losses for CDC Hilose coarse bulgur increased, though not significantly,

from 110 to 120°C, however, the jump in temperature from 120 to 130°C resulted in a significant increase in cooking losses (Table A.11). The linear regression model for CDC Hilose coarse bulgur was $LS = (0.034/°C)T_{SS} - 1.25$ ($p = 0.004$, $aR^2 = 0.87$); where LS is cooking losses (%) and T_{SS} is the temperature of the superheated steam from 110 to 130°C. For CDC Hilose fine bulgur a significant increase in cooking losses resulted from raising the SS temperature from 110 to 120°C, and an insignificant increase when the temperature was further raised to 130°C (Table A.11). The linear model for CDC Hilose fine bulgur was $LS = (0.050/°C)T_{SS} - 1.98$ ($p = 0.0008$, $aR^2 = 0.94$) (Figure 5.14).

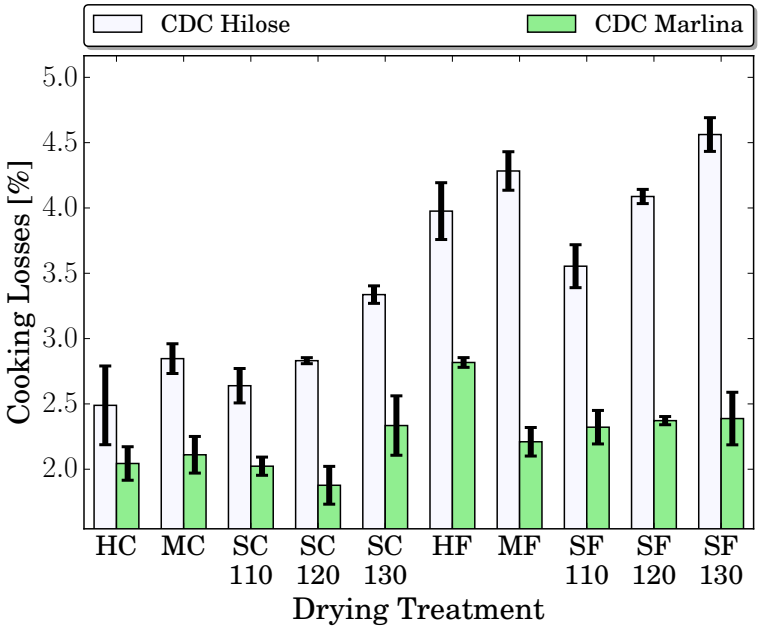


Figure 5.13: Cooking loss (% w/w) for bulgur. Error bars are standard deviation. Abbreviations: Drying treatments are denoted by the first letter under the corresponding bar: H - hot air dried, M - microwave dried, S - superheated steam dried. Bulgur size is indicated by the second letter C - coarse bulgur, F - fine bulgur. The numbers 110, 120, and 130 are temperatures in °C for superheated steam.

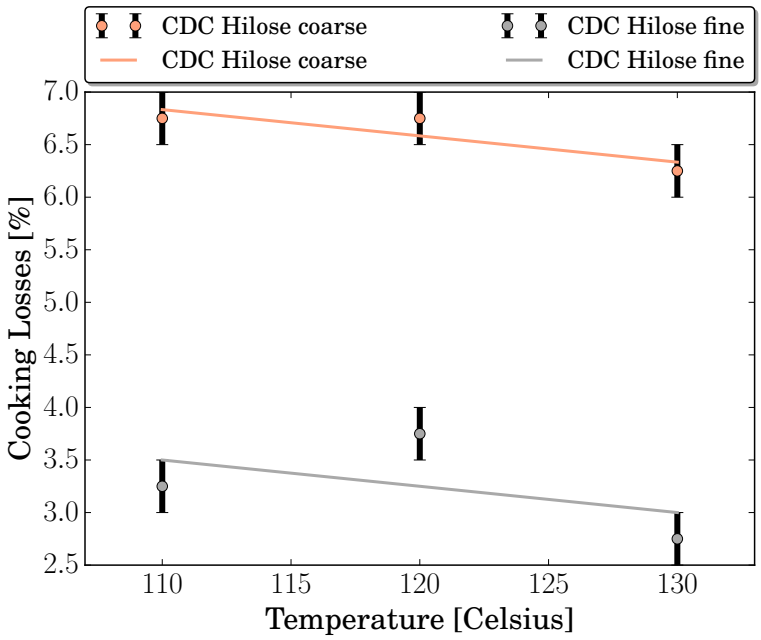


Figure 5.14: The values for bulgur (coarse and fine) cooking losses values, for CDC Hilose and CDC Marlina. Superheated steam (SS) at temperatures 110, 120, and 130°C was fit as the independent variable and cooking losses values as dependent variables. Points are the means of the values and error bars are standard error values.

5.11 β-glucans

5.11.1 Total β-glucans

Final moisture content was not correlated with values for total β-glucans ($P > 0.05$, aR^2 approx. 0).

Total β-glucans were significantly higher in CDC Hilose variety than in CDC Marlina variety ($p = 0.04$). Drying treatments had significant effects on total β-glucans for both varieties, $p = 0.03$ and $p = 0.0004$ for CDC Hilose and CDC Marlina, respectively (Table 5.5). The p values reported do not include raw (not cooked) barley. Including the values for raw barley resulted in lower p-values.

5.11.2 Soluble β-glucans

Soluble β-glucans make up a portion of the total β-glucans. Although regression tests for total β-glucans showed no correlation between final moisture content and total β-glucans, the regression tests for the soluble portion had lower p-values and higher aR^2 values: CDC Hilose ($p = 0.003$, $aR^2 = 0.65$) and CDC Marlina ($p = 0.01$, $aR^2 = 0.52$). A regression test for soluble β-glucans as a function of porosity returned a good model for both CDC Hilose and CDC Marlina. The model for CDC Hilose was $S\beta = 36.06P - 15.54$ ($p \ll 0.05$, $aR^2 = 0.89$); where Sβ is the percent soluble β-glucans of the total β-glucans and P is porosity (no units). For CDC Marlina the model was $S\beta = 83.55P - 36.75$ ($p \ll 0.05$, $aR^2 = 0.87$) (Figure 5.15).

Under the conditions of testing, the soluble β-glucans portion of the total β-glucans was significantly higher in CDC Marlina than CDC Hilose ($p \ll 0.05$). The soluble portion of the total β-glucans was significantly influenced by drying treatment in both varieties, $p = 0.0007$ and $p = 0.003$ for CDC Hilose and CDC Marlina, respectively (Table 5.5).

5.12 Vitamin E

No correlation was found between final moisture content and values for tocochromanol content for any of the tocopherols or tocotrienols.

With the sole exception of αT3, CDC Hilose had higher values for tocochromanol content by mass, on average, than CDC Marlina; however, significant differences of tocochromanol content between the varieties were noted only in δT, βT3, and γT3 ($p \ll 0.05$).

Table 5.5: Total β-glucans for dried barley, and soluble β-glucans for fine bulgur, extracted at 40°C. CDC Hilose: above dashed line, CDC Marlina: below dashed line.

Variety	Drying treatment	Total β-glucans DWB w/w % ± SD	Water soluble β-glucans % of β-glucans % ± SD	Water soluble β-glucans DWB w/w % ± SD
CDC Hilose	HA	$7.21 \pm 0.01^{ab;BCDE}$	$3.15 \pm 0.15^{c;F}$	$0.23 \pm 0.01^{c;E}$
	MW	$7.38 \pm 0.02^{ab;AB}$	$5.13 \pm 0.49^{b;EF}$	$0.38 \pm 0.04^{b;DE}$
	SS 110°C	$7.34 \pm 0.02^{ab;ABC}$	$5.91 \pm 0.30^{ab;DEF}$	$0.43 \pm 0.02^{ab;DE}$
	SS 120°C	$7.42 \pm 0.02^{a;A}$	$5.08 \pm 0.17^{b;EF}$	$0.38 \pm 0.01^{b;DE}$
	SS 130°C	$7.18 \pm 0.13^{b;CDEF}$	$7.21 \pm 0.47^{a;DE}$	$0.52 \pm 0.03^{a;D}$
	Raw	$7.16 \pm 0.05^{b;CDEF}$		
CDC Marlina	HA	$7.09 \pm 0.00^{3;DEF}$	$8.49 \pm 0.54^{2;CD}$	$0.60 \pm 0.04^{2;CD}$
	MW	$7.27 \pm 0.02^{2;ABCD}$	$10.94 \pm 0.06^{2;BC}$	$0.80 \pm 0.00^{2;BC}$
	SS 110°C	$7.08 \pm 0.00^{3;EF}$	$12.83 \pm 1.04^{2;B}$	$0.91 \pm 0.07^{2;B}$
	SS 120°C	$7.41 \pm 0.07^{1;A}$	$11.64 \pm 1.09^{2;BC}$	$0.86 \pm 0.08^{2;B}$
	SS 130°C	$6.99 \pm 0.01^{3;F}$	$17.62 \pm 1.88^{1;A}$	$1.23 \pm 0.13^{1;A}$
	Raw	$7.04 \pm 0.01^{3;EF}$		

[a-c] for CDC Hilose (above dashed horizontal line), [1-3] for CDC Marlina (below dashed horizontal line), and [A-F] for both varieties; values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$).
Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

Tables 5.6, 5.7, 5.8, and 5.9 contain the mean values for tocochromanol content with SD, % retention, and % of total tocochromanols.

For regression models of tocochromanol content correlation to SS drying temperatures, only CDC Marlina α-tocopherol and γ-tocotrienol values fit with both a p-value less than 0.05 and an aR^2 value greater than 0.8. For CDC Marlina α-tocopherol the linear model was $TC = (-0.10\,(\mu g/g)/°C)T_{SS} + 17.27\,\mu g$ ($p = 0.002$, $aR^2 = 0.91$); where TC is tocochromanol content (µg/g) and T_{SS} is the temperature

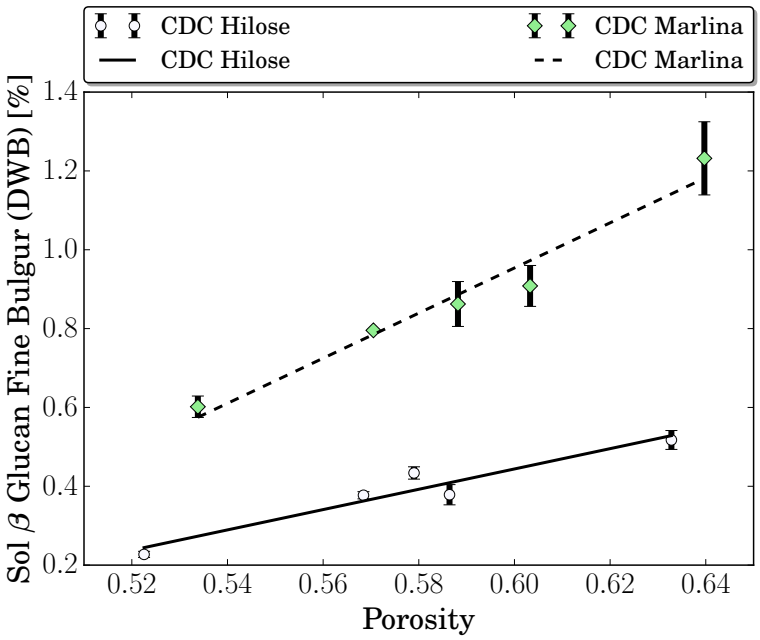


Figure 5.15: The values for soluble β-glucans extracted from fine bulgur, for CDC Hilose and CDC Marlina. Porosity values were fit as the independent variable and the values of extracted β-glucans as dependent variables. Points are the means of the values and error bars are standard error values.

of the superheated steam from 110 to 130°C. For CDC Marlina γ-tocotrienol the linear regression model was $TC = (-0.01\,(\mu g/g)/°C)T_{SS} + 7.74\,\mu g$ ($p = 0.002$, $aR^2 = 0.91$).

Table 5.6: Vitamin E tocopherol (T) values for CDC Hilose; mean, SD, % retained after drying, % of total tocochromanols

	Drying treatment	**αT**	**βT**	**γT**	**δT**	**Total T**
Mean µg/g	HA	4.49[b]	0.58[b]	3.44[b]	1.19[a]	9.70[b]
SD		0.02	0.06	0.11	0.57	0.38
% retained		37.69	54.72	80.26	61.11	50.51
% of Total		10	1	8	3	22
Mean µg/g	MW	7.48[a]	0.92[a]	3.64[b]	1.28[a]	13.32[a]
SD		0.29	0.01	0.19	0.40	0.09
% retained		62.90	86.79	85.00	65.45	69.38
% of Total		12	1	6	2	21
Mean µg/g	SS 110	7.76[a]	1.07[a]	4.52[a]	1.44[a]	14.79[a]
SD		0.17	0.02	0.03	0.12	0.34
% retained		65.21	100.94	105.53	73.75	77.05
% of Total		12	2	7	2	23
Mean µg/g	SS 120	5.00[b]	1.05[a]	4.65[a]	1.39[a]	12.09[a,b]
SD		0.04	0.06	0.01	1.63	1.74
% retained		42.01	99.06	108.56	71.19	62.99
% of Total		8	2	8	2	20
Mean µg/g	SS 130	4.87[b]	1.03[a]	4.74[a]	1.36[a]	12.00[a,b]
SD		0.28	0.05	0.37	0.05	0.75
% retained		40.92	97.17	110.66	69.66	62.52
% of Total		8	2	8	2	20
Mean µg/g	Raw	11.90	1.06	4.28	1.95	19.20
SD		0.54	0.03	0.26	0.66	0.11
% of Total		16	1	6	3	26

[a-c] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$).
Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

Table 5.7: Vitamin E tocotrienol (T3) values for CDC Hilose; mean, SD, % retained after drying, % of total tocochromanols

	Drying treatment	**αT3**	**βT3**	**γT3**	**δT3**	**Total T3**
Mean µg/g	HA	15.95[c]	10.65[a]	7.51[a]	trace	34.11[b]
SD		0.14	0.07	0.10		0.32
% retained		45.98	88.32	76.71		60.33
% of Total		36	24	17		77
Mean µg/g	MW	28.91[b]	11.55[a]	8.62[a]	trace	49.08[a]
SD		1.44	0.49	0.55		2.48
% retained		83.32	95.78	88.03		86.79
% of Total		46	19	14		79
Mean µg/g	SS 110	32.37[a]	11.21[a]	8.20[a]	trace	51.78[a]
SD		0.10	0.10	0.14		0.34
% retained		93.29	92.96	83.78		91.57
% of Total		49	17	12		78
Mean µg/g	SS 120	28.00[b]	11.20[a]	8.10[a]	trace	47.3[a]
SD		0.17	0.32	0.15		0.64
% retained		80.7	92.87	82.76		83.65
% of Total		47	19	14		80
Mean µg/g	SS 130	27.79[b]	11.13[a]	8.00[a]	trace	46.92[a]
SD		0.84	0.46	0.41		1.71
% retained		80.09	92.29	81.74		82.98
% of Total		47	19	14		80
Mean µg/g	Raw	34.7	12.06	9.79	trace	56.54
SD		0.06	0.09	0.17		0.20
% of Total		46	16	13		75

Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

Table 5.8: Vitamin E tocopherol (T) values for CDC Marlina; mean, SD, % retained after drying, % of total tocochromanols

	Drying treatment	**αT**	**βT**	**γT**	**δT**	**Total T**
Mean µg/g	HA	4.54[c,d]	0.51[b]	2.93[b]	trace	7.99[c]
SD		0.00	0.16	0.00		0.16
% retained		43.49	60.00	76.06		52.71
% of Total		12	1	8		21
Mean µg/g	MW	6.82[a]	0.97[a]	4.29[a]	trace	12.08[a]
SD		0.11	0.13	0.00		0.24
% retained		65.26	114.12	111.30		79.72
% of Total		12	2	8		22
Mean µg/g	SS 110	6.37[b]	1.00[a]	4.23[a]	trace	11.60[a]
SD		0.10	0.01	0.15		0.26
% retained		60.99	117.65	109.70		76.56
% of Total		11	2	8		21
Mean µg/g	SS 120	4.90[c]	0.95[a]	4.25[a]	trace	10.10[b]
SD		0.02	0.10	0.56		0.68
% retained		46.91	111.76	110.22		66.66
% of Total		9	2	8		19
Mean µg/g	SS 130	4.36[d]	0.95[a]	4.33[a]	trace	9.64[b]
SD		0.13	0.03	0.00		0.16
% retained		41.74	111.76	112.29		63.63
% of Total		8	2	8		18
Mean µg/g	Raw	10.44	0.85	3.86	trace	15.15
SD		0.18	0.10	0.04		0.24
% of Total		15.01	1.22	5.54		21.77

Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

Table 5.9: Vitamin E tocotrienol (T3) values for CDC Marlina; mean, SD, % retained after drying, % of total tocochromanols

	Drying treatment	**αT3**	**βT3**	**γT3**	**δT3**	**Total T3**
Mean µg/g	HA	17.41[b]	4.73[a]	6.26[c]	trace	28.4[b]
SD		0.39	0.02	0.00		0.37
% retained		42.92	81.78	77.45		52.18
% of Total		48	13	17		78
Mean µg/g	MW	32.67[a]	5.07[a]	7.15[a]	trace	44.89[a]
SD		0.04	0.00	0.08		0.04
% retained		80.53	87.66	88.41		82.46
% of Total		57	9	13		79
Mean µg/g	SS 110	33.14[a]	4.92[a]	6.48[b]	trace	44.54[a]
SD		0.05	0.04	0.02		0.11
% retained		81.69	85.06	80.14		81.82
% of Total		59	9	12		80
Mean µg/g	SS 120	32.87[a]	4.87[a]	6.35[b,c]	trace	44.09[a]
SD		0.30	0.02	0.01		0.33
% retained		81.03	84.20	78.53		80.99
% of Total		61	9	12		82
Mean µg/g	SS 130	30.84[a]	4.87[a]	6.25[c]	trace	41.96[a]
SD		1.80	0.30	0.06		2.16
% retained		76.02	84.20	77.29		77.08
% of Total		60	9	12		81
Mean µg/g	Raw	40.57	5.78	8.09	trace	54.44
SD		0.27	0.08	0.10		0.45
% of Total		58.30	8.31	11.62		78.23

Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

6. *Discussions*

Final moisture content was not found to be a significant factor with OLS models for differences in the values obtained from testing the end products except for cooking time and soluble β-glucans. Cooking time is, at least in part, a test of the properties of rehydration and a higher initial moisture content would hasten the process of rehydration when all other parameters are held equal. Another variable found to affect the rate of rehydration was porosity and the results for cooking time demonstrated a more pronounced correlation to porosity than to initial moisture content.

The method used for analysis of particle size distribution after steel cutting and Ro-tapping was compared to the ASABE standard for expressing fineness of feed materials (ASABE 2008). The fundamental difference between the two methods is that the ASABE standard relies on the geometric mean of the aperture size of the tray through which the product passed and the aperture size of the tray through which the product did not pass. The modulus of fineness calculations given in Equations 4.2 to 4.4 rely only on the aperture size of the tray through which the product did not pass. This difference between the two methods results in a slight change to the ordering of the outcomes and the pairwise comparisons. The selection of trays for this study resulted in the omission of tray sizes between coarse and fine bulgur sizes, as well as from fine bulgur to the residue size. The ASABE standard significantly favours

the proportion of the residue size, whereas the calculations used in Equations 4.2 to 4.4 weight the ordering of the coarse bulgur proportion more significantly than the ordering of the residue sized particles. The proportion of residue was, for all classes of variety and treatment, much smaller than that of the coarse bulgur. Moreover, the coarse bulgur is of interest for this study, whereas, the residue is not. Therefore, the method with heavier weighting to the coarse bulgur was used, that is, the modulus of fineness (MF) in Equations 4.2 to 4.4.

The method of testing used for soluble β-glucans did not include particle size reduction or enzyme treatment with amylase to remove the starch from the β-glucans and the test results may not, therefore, account for all soluble β-glucans but only for those that came into the water solution during the cooking and incubation procedures. Whereas moisture content regression analysis provided significant differences with non-explanatory aR^2 values, the porosity regression analysis provided regression models with explanatory aR^2 values. Products with higher porosity resulted in more soluble β-glucans in the cooking water. If the product is cooked in excess water, then those β-glucans will be lost if the water is drained.

Kernels with higher porosity values were more brittle and had lower MF values than samples with lower porosity values. For large scale production, the energy required for cutting may be reduced as opposed to kernels with less porosity. The additional benefits of less cooking time and more soluble β-glucans in the cooking water have already been discussed above.

For SS treated barley the resulting barley and bulgur products were of a lighter shade when treated with higher temperatures. Microwave dried barley and bulgur had a lighter shade than hot air dried and was either comparable to the higher or

intermediate temperatures for SS dried products. Darker products can be an indication of damage and oxygenation. In some markets, the consumer may prefer a lighter product, whereas in other markets the consumer may well prefer a darker product. Alternatively, a consumer may have less of a bias towards colour and more of a bias to texture, chewiness, and taste, which were not tested for in this study.

The porosity did not correlate to more water absorption for coarse bulgur but fine bulgur, with higher porosity, generally had higher rates of absorption. With known rates of absorption for a product, the cooking instructions can be tailored, so that excess water is not used. By not draining the water used for cooking bulgur, the losses which include soluble β-glucans can be minimized. Bulk density values can be used to provide cooking instructions by volume and not by mass as most households are accustomed to measuring ingredients for cooking by volume and not by mass.

Higher porosity resulted in higher levels of soluble β-glucans in the cooking water, and this will result in a more viscous end product. The cooked product will, as such, have a different texture and may or may not be preferred by the consumer. Higher levels of soluble β-glucans directly benefit the GI of the meal being consumed, whereas, non-soluble β-glucans enhance the gastrointestinal response for the next meal (Thondre et al. 2012).

Vitamin E tocopherols were more susceptible to damage by heat than tocotrienols. Higher temperatures generally resulted in less tocochromanol retention. As noted by Qureshi et al. (1986), Sen et al. (2004), Berbée et al. (2012), Trias and Tan (2012), and Viola et al. (2012) tocopherols tend to interfere with tocotrienol absorption and maximum benefit is gained from tocochromanols when the tocopherol proportion is lower with a strong preference for less α-tocopherol. The higher drying temperatures

for SS (120 and 130°C) provide the conditions necessary for lowering the ratio of tocopherols. The tocopherols are found in the embryo of the barley grain and the tocotrienols in the aleurone layer. From this study, it can not be determined if the better retention of the tocotrienols was a result of being less susceptible to damage than their tocopherol counterparts or if the aleurone layer offered protection from degradation that was not afforded the tocopherols in the embryo.

Although drying curves were not examined in this study, the higher temperature settings for SS resulted in shorter processing times and, for production, this translates into the ability to process more product in a given period or to reduce the size of the drying equipment.

7. *Conclusions*

In this study barley grains of two varieties, CDC Hilose and CDC Marlina, were cooked in a pressure cooker for 15 min and then dried using three different techniques, hot air, microwave, and superheated steam. Superheated steam drying was repeated at three temperatures, 110, 120, and 130°C. The targeted end moisture was 9 % but the actual end moistures after drying ranged from 9.7 to 14.7 %. The dried barley was tested for colour with the L* a* b* colour scale, bulk density, kernel mass, kernel density, total β-glucans, and tocochromanol content. Porosity was calculated from the average bulk density and kernel density values. The dried barley was then steel cut and Ro-tapped and divided into three portions, by size: coarse bulgur, fine bulgur, and residue. The size distribution was analyzed. The colours of the two bulgur sizes were measured and then cooked. During and after cooking three parameters were measured; cooking time to gelatinization, water absorption during cooking, and cooking losses. The fine bulgur was cooked and agitated at 40°C in the cooking water, and afterwards, the water was analyzed for soluble β-glucans.

Influence of variations in final moisture content

The discrepancies in final moisture content were noted as significant only in the cooking time and soluble β-glucans tests. Both of these tests are functions of rehydration.

Higher moisture content was related to less cooking time and a higher content of soluble β-glucans in the water. However, after an additional analysis was performed, it was found that differences in porosity were explanatory for the variations in cooking time and extracted soluble β-glucans.

Groups of functions as explanations of results

The values obtained from the tests conducted can be grouped as functions of porosity, treatment, variety, and for SS treatments temperature.

Size distribution

Modulus of fineness values was in general related to porosity with higher values of porosity related to lower MF values. The MF values for both varieties were lowest for SS 130 and highest for hot air dried barley. The MF values for CDC Hilose SS 130 were 8% lower than hot air dried MF values, and for CDC Marlina the difference was 11%. When SS treatments were isolated the MF values were related by linear regression to the temperature of treatment with increasing temperature from 110 to 130°C producing a predictable decline in MF values.

Colour

Microwave dried barley and bulgur were lighter in colour than their counterparts dried with hot air. For SS dried barley the trend was for higher temperatures to produce end products with a lighter colour. For SS treatments the change in lightness of colour was a linear relationship to SS temperature. Microwave dried barley and bulgurs were lighter in colour than SS 120 but darker than SS 130.

Bulk density

The bulk density values for both varieties were highest for hot air dried and lowest for SS 130 treatments. On a dry mass basis, the difference between the two extremes was 42% for CDC Hilose and 46% for CDC Marlina. For SS treatments the change in bulk densities was linearly predictable with a decrease of 5.3 and 5.9 (g/L)/°C for CDC Hilose and CDC Marlina, respectively when measured as dry basis.

1000 kernel mass

Kernel mass was not affected by treatment but rather by variety; the kernel mass for CDC Hilose was higher than that of CDC Marlina. The 1000 kernel mass for CDC Hilose ranged from 32.56 to 33.21 g with no significant differences between treatments. For CDC Marlina the 1000 kernel mass was in the range of 31.37 to 32.17 g also with no significant differences between treatments.

Kernel density

Kernel density was found to be a function of treatment and for CDC Marlina variety the SS treatments kernel densities were also a function of temperature with a rise in temperature producing a predictable decline in kernel density of 8.8 mg/cm^3 per increase in °C from 110 to 130°C. Hot air dried barley had higher kernel densities than microwave dried. For CDC Hilose variety, MW (1.41 g/cm^3) and SS 110 (1.45 g/cm^3) were comparable, whereas, for CDC Marlina hot air dried (1.50 g/cm^3) was comparable to SS 110 (1.51 g/cm^3) while MW and SS 130 both had values of 1.33 g/cm^3.

Cooking time

The waxy variety, CDC Marlina, needed significantly less time to cook (from 1 to 7 min) than the high amylose variety, CDC Hilose (from 2.75 to 12.75 min). Cooking time was a function of size and porosity. Hot air dried barley had the lowest level of porosity and superheated steam at 130°C the highest. The amount of time needed to cook the hot air dried bulgur as opposed to SS 130 was approximately double for CDC Hilose variety either coarse or fine but 2.5 and 3.75 times more for CDC Marlina coarse and fine bulgur, respectively. Hot air and microwave dried bulgurs took longer to cook than bulgurs made from any of the three treatments for SS. Raising the temperature of the SS treatments insignificantly shortened the required cooking time.

Cooking water absorption

Cooking water absorption was a function of bulgur size, treatment, and temperature for SS treatments. The range of cooking water absorbed by bulgur was from 72 to 162 % for CDC Marlina coarse SS 110 and CDC Marlina Fine SS 130, respectively. Fine bulgur absorbed significantly more water while cooking than coarse bulgur. Superheated steam treatments resulted in a predictable rise in water absorption corresponding to increases in temperature. That rise in water absorption was 0.95, 1.34, 1.66, and 2.31 %/°C for CDC Hilose coarse, CDC Hilose fine, CDC Marlina coarse, and CDC Marlina fine, respectively.

Cooking losses

Losses from cooked bulgurs ranged from 1.88 to 4.56 %. Losses during cooking were found to be affected by variety and by size. CDC Hilose had significantly more cooking losses than CDC Marlina, and fine bulgur had significantly more cooking losses than coarse bulgur. For CDC Marlina coarse bulgur there were no significant differences based on drying method, however, for CDC Marlina fine bulgur and CDC Hilose bulgurs significant differences were noted. Generally, microwave dried bulgur had insignificantly more losses than hot air dried bulgur, but for CDC Marlina fine bulgur the trend was reversed, and hot air dried bulgur had significantly more losses than microwave dried bulgur. For SS treatments the trend was for higher temperatures to have more losses; however, predictable models were only obtained for CDC Hilose bulgurs with a predicted increase in losses of 0.034 and 0.050 %/°C for CDC Hilose coarse and CDC Hilose fine, respectively.

Total β-glucans

Total β-glucans were not as susceptible to losses during the pre-treatment cooking process and subsequent drying treatment as other components in the barley. For this reason, the percent w/w values were generally higher for processed barley than they were for raw barley except CDC Marlina SS 130 which was insignificantly less than raw CDC Marlina barley. Generally, CDC Hilose had more total β-glucans than CDC Marlina. Microwave dried barley had more total β-glucans w/w than hot air dried barley. As the destruction of polysaccharides is a function of temperature and time at elevated temperatures it was observed that both SS 110 and SS 130 had less total β-glucans than SS 120.

Soluble β-glucans

For CDC Hilose the soluble β-glucans ranged from 3.15 to 7.21 % of total β-glucans for hot air dried and SS 130, respectively. These values were significantly lower than those for CDC Marlina, which ranged from 8.49 to 17.62 % of total β-glucans also for hot air dried and SS 130, respectively. Soluble β-glucans were found to be a function of variety and porosity. More porous grains had higher values for soluble β-glucans. Porosity is a function of the drying method.

Vitamin E

The α tocopherol proportion of total tocochromanols was lowest in SS 120 and SS 130 drying methods at 8 % for CDC Hilose and 8 and 9 % for CDC Marlina SS 120 and SS 130, respectively. These treatments had totol tocopherol contents of less than 20 %, which is desirable.

Recommended method

Based on the desire for short preparation times, favourable tocochromanol ratios, higher values for soluble β-glucans, and high rates of water absorption while cooking the recommended method for drying barley to make bulgur would be to use superheated steam at either 120 or 130°C. In addition to receiving a higher quality product the drying times for the selected methods are less when compared to the other methods tested, and this allows for higher rates of productivity with less initial capital expenditures.

8. *Recommendations for future research*

For barley bulgur production the effects of different drying techniques on palate appeal would need to be studied, as well as shelf life. Factors that could affect shelf life would include final moisture levels, packaging techniques, and storage conditions.

Pursuing the technique of superheated steam drying could also be done under conditions of reduced pressure, which has often been associated with enhanced product quality. Furthermore, superheated steam processing may offer benefits of simultaneous gelatinization and drying resulting in the elimination of the pre-treatment cooking phase. If superheated steam processing does not offer simultaneous gelatinization, then a dryer/cooker that utilizes the heat of the drying phase for the cooking process could be designed. Alternatively, if the pretreatment and drying processes can be combined the heat from processing could be used to heat the facility.

A techno-economic analysis involving the full cost of production and market readiness would help establish the critical price needed to justify production. Alternatively, advertising with an emphasis on the health benefits would raise awareness, acceptance, and demand.

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Appendices

A.

Table A.1: Values of colour lightness (L*) for CDC Hilose bulgur (coarse and fine), prepared using three drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	**Drying treatment**	**L***	**Size**	**Drying treatment**	**L***
Coarse	HA	$40.97 \pm 0.28^{b,c}$	Fine	HA	42.59 ± 0.11^{d}
	MW	43.71 ± 0.58^{a}		MW	45.58 ± 0.19^{b}
	SS 110°C	39.82 ± 0.09^{c}		SS 110°C	$43.97 \pm 0.69^{c,d}$
	SS 120°C	42.22 ± 0.30^{b}		SS 120°C	$44.28 \pm 0.25^{b,c}$
	SS 130°C	44.19 ± 0.42^{a}		SS 130°C	47.65 ± 0.21^{a}

[a-d] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.2: Values of colour lightness (L*) for CDC Marlina bulgur (coarse and fine), prepared using three drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size[!1]	Drying treatment[!1]	L*	Size[!1]	Drying treatment[!1]	L*
Coarse	HA	$41.58 \pm 0.21^{b,c}$	Fine	HA	43.39 ± 0.33^{c}
	MW	44.67 ± 0.47^{a}		MW	46.14 ± 0.50^{b}
	SS 110°C	40.23 ± 0.41^{c}		SS 110°C	43.12 ± 0.88^{c}
	SS 120°C	42.25 ± 0.25^{b}		SS 120°C	$44.94 \pm 0.03^{b,c}$
	SS 130°C	45.92 ± 0.28^{a}		SS 130°C	49.49 ± 0.33^{a}

[a-d] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.3: Values of colour lightness (L*) for dried barley (CDC Hilose and CDC Marlina), dried with three drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

CDC Hilose		CDC Marlina	
Drying treatment[!1]	L*	Drying treatment[!1]	L*
HA	37.94 ± 0.36^{c}	HA	37.31 ± 1.04^{d}
MW	40.42 ± 0.31^{a}	MW	41.39 ± 0.18^{b}
SS 110°C	36.73 ± 0.27^{d}	SS 110°C	38.70 ± 0.11^{c}
SS 120°C	39.16 ± 0.20^{b}	SS 120°C	39.48 ± 0.13^{c}
SS 130°C	40.72 ± 0.08^{a}	SS 130°C	43.10 ± 0.33^{a}

[a-d] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.4: Mean values for colour analysis (L*, a*, b*) of dried barley and raw bulgur with corresponding ΔE_{00} values for comparison to white colour and sums of ΔE_{00} and L* values showing a linear relationship. Barley was dried using three drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Variety	**Drying treatment**	**Size Designation**[!1]	**Delta E** ΔE_{00}[!2]	**L***	**a***	**b***	**Sum** L* + ΔE_{00}
CDC Hilose	HA	Whole	50.83	37.94	6.99	19.88	88.77
		Coarse	47.64	40.96	6.49	19.08	88.60
		Fine	46.03	42.58	6.29	18.98	88.61
	MW	Whole	48.58	40.42	7.37	21.74	89.00
		Coarse	45.31	43.71	6.98	21.25	89.02
		Fine	43.49	45.58	6.64	20.90	89.07
	SS 110°C	Whole	52.14	36.73	7.78	19.77	88.87
		Coarse	49.03	39.82	7.57	20.26	88.85
		Fine	44.89	43.96	6.76	20.05	88.85
	SS 120°C	Whole	49.67	39.16	7.61	20.09	88.83
		Coarse	46.77	42.22	7.46	21.22	88.99
		Fine	44.77	44.28	7.09	21.10	89.05
	SS 130°C	Whole	48.34	40.72	7.74	21.92	89.06
		Coarse	45.03	44.19	7.30	22.33	89.22
		Fine	41.73	47.64	6.74	21.62	89.37
CDC Marlina	HA	Whole	49.98	38.70	6.69	19.49	88.68
		Coarse	47.11	41.58	6.45	19.64	88.69
		Fine	45.30	43.38	6.23	19.30	88.68
	MW	Whole	47.58	41.39	7.24	21.43	88.97
		Coarse	44.41	44.66	6.82	21.31	89.07
		Fine	43.03	46.14	6.62	21.30	89.17
	SS 110°C	Whole	51.52	37.31	7.49	19.83	88.83
		Coarse	48.51	40.23	7.17	19.69	88.74
		Fine	45.72	43.12	6.85	20.14	88.84
	SS 120°C	Whole	49.26	39.48	7.29	19.63	88.74
		Coarse	46.65	42.24	6.97	20.84	88.89
		Fine	44.15	44.94	6.74	21.36	89.09
	SS 130°C	Whole	46.00	43.10	6.99	22.16	89.10
		Coarse	43.39	45.92	6.61	22.45	89.31
		Fine	40.10	49.49	6.14	21.95	89.59

[!1] The word whole designates dried barley before steel cutting. Coarse and fine are bulgur size designations, after steel cutting and Ro-tapping.

[!2] Each colour with L*, a*, and b* values was compared to white L* = 100, a* = b* = 0, using the ΔE_{00} algorithm.

Table A.5: Bulk density values after drying grain using three techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Variety	**Drying treatment**	**Bulk density (as measured) [g/L] ± SD**	**Bulk density (dry mass basis) [g/L] ± SD**
CDC Hilose	HA	$789.93 \pm 1.22^{a;A}$	$713.15 \pm 1.10^{a;A}$
	MW	$661.13 \pm 1.72^{c;E}$	$582.72 \pm 1.52^{c;E}$
	SS 110°C	$715.27 \pm 2.66^{b;C}$	$610.16 \pm 2.27^{b;C}$
	SS 120°C	$656.33 \pm 3.86^{c;E}$	$583.51 \pm 3.43^{c;E}$
	SS 130°C	$583.67 \pm 7.45^{d;G}$	$503.82 \pm 6.43^{d;G}$
CDC Marlina	HA	$774.20 \pm 2.09^{1;B}$	$698.75 \pm 1.88^{1;B}$
	MW	$644.33 \pm 0.81^{3;F}$	$572.78 \pm 0.72^{3;F}$
	SS 110°C	$696.47 \pm 0.58^{2;D}$	$598.26 \pm 0.50^{2;D}$
	SS 120°C	$642.87 \pm 1.67^{3;F}$	$565.85 \pm 1.47^{4;F}$
	SS 130°C	$554.27 \pm 2.19^{4;H}$	$479.91 \pm 1.90^{5;H}$

[a-d] for CDC Hilose (above dashed horizontal line), [1-5] for CDC Marlina (below dashed horizontal line), and [A-H] for both varieties; values with different superscripts are significantly different (Tukey's HSD $p < 0.05$).

Table A.6: Kernel density values, dry mass basis, after drying grain using three techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Variety	**Drying treatment**	**Kernel density (dry weight) g/cm^3 ± SD**
CDC Hilose	HA	$1.49 \pm 0.00^{a,A}$
	MW	$1.41 \pm 0.00^{bc,C}$
	SS 110°C	$1.45 \pm 0.01^{b,B}$
	SS 120°C	$1.35 \pm 0.02^{d,DE}$
	SS 130°C	$1.37 \pm 0.03^{cd,CDE}$
CDC Marlina	HA	$1.50 \pm 0.00^{1,A}$
	MW	$1.33 \pm 0.02^{3,E}$
	SS 110°C	$1.51 \pm 0.00^{1,A}$
	SS 120°C	$1.37 \pm 0.02^{2,CD}$
	SS 130°C	$1.33 \pm 0.01^{3,E}$

[a-d] for CDC Hilose (above dashed horizontal line), [1-3] for CDC Marlina (below dashed horizontal line), and [A-E] for both varieties; values with different superscripts are significantly different (Tukey's HSD $p < 0.05$).

Table A.7: Cooking time in min for CDC Hilose bulgurs (coarse and fine) prepared using different drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	**Drying treatment**	**Cooking time min ± SD**	**Size**	**Drying treatment**	**Cooking time min ± SD**
Coarse	HA	12.75 ± 1.06^{a}	Fine	HA	5.50 ± 0.00^{a}
	MW	7.75 ± 1.06^{b}		MW	$4.25 \pm 0.35^{a,b}$
	SS 110°C	6.75 ± 0.35^{b}		SS 110°C	$3.25 \pm 0.35^{b,c}$
	SS 120°C	6.75 ± 0.35^{b}		SS 120°C	$3.75 \pm 0.35^{b,c}$
	SS 130°C	6.25 ± 0.35^{b}		SS 130°C	2.75 ± 0.35^{c}

[a-c] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.8: Cooking time in min for CDC Marlina bulgurs (coarse and fine) prepared using different drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	Drying treatment	Cooking time min ± SD	Size	Drying treatment	Cooking time min ± SD
Coarse	HA	7.00 ± 0.00^{a}	Fine	HA	3.75 ± 0.35^{a}
	MW	5.50 ± 0.00^{b}		MW	2.00 ± 0.00^{b}
	SS 110°C	3.25 ± 0.35^{c}		SS 110°C	$1.50 \pm 0.00^{b,c}$
	SS 120°C	3.75 ± 0.35^{c}		SS 120°C	$1.75 \pm 0.35^{b,c}$
	SS 130°C	2.75 ± 0.35^{c}		SS 130°C	1.00 ± 0.00^{c}

[a-c] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.9: Percentage w/w of water absorption while cooking CDC Hilose bulgurs (coarse and fine) prepared using different drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	Drying treatment	Water absorption % ± SD	Size	Drying treatment	Water absorption % ± SD
Coarse	HA	$100.55 \pm 0.07^{a,b}$	Fine	HA	$114.44 \pm 1.59^{b,c}$
	MW	$97.78 \pm 0.74^{a,b}$		MW	$125.92 \pm 5.66^{a,b}$
	SS 110°C	82.92 ± 1.55^{c}		SS 110°C	106.92 ± 0.56^{c}
	SS 120°C	97.30 ± 1.06^{b}		SS 120°C	$122.88 \pm 0.25^{a,b}$
	SS 130°C	101.87 ± 1.10^{a}		SS 130°C	133.76 ± 3.17^{a}

Abbreviations for drying treatments: HA - hot air dried, MW - microwave dried, SS - superheated steam dried.

[a-c] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.10: Percentage w/w of water absorption while cooking CDC Marlina bulgurs (coarse and fine) prepared using different drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	**Drying treatment**	**Water absorption % ± SD**	**Size**	**Drying treatment**	**Water absorption % ± SD**
Coarse	HA	89.73 ± 1.48^{b}	Fine	HA	123.41 ± 1.90^{b}
	MW	101.87 ± 0.60^{a}		MW	125.74 ± 5.80^{b}
	SS 110°C	71.96 ± 0.75^{d}		SS 110°C	116.26 ± 3.42^{b}
	SS 120°C	85.46 ± 1.06^{c}		SS 120°C	127.25 ± 1.91^{b}
	SS 130°C	105.11 ± 1.10^{a}		SS 130°C	162.41 ± 6.25^{a}

[a-d] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.11: Percentage w/w of cooking losses while cooking CDC Hilose bulgurs (coarse and fine) prepared using different drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	**Drying treatment**	**Cooking losses % ± SD**	**Size**	**Drying treatment**	**Cooking losses % ± SD**
Coarse	HA	2.49 ± 0.30^{b}	Fine	HA	$3.98 \pm 0.22^{a,b}$
	MW	$2.85 \pm 0.11^{a,b}$		MW	4.28 ± 0.15^{a}
	SS 110°C	2.64 ± 0.13^{b}		SS 110°C	3.55 ± 0.16^{b}
	SS 120°C	$2.83 \pm 0.02^{a,b}$		SS 120°C	$4.09 \pm 0.05^{a,b}$
	SS 130°C	3.34 ± 0.07^{a}		SS 130°C	4.56 ± 0.13^{a}

[a-b] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.

Table A.12: Percentage w/w of cooking losses while cooking CDC Marlina bulgurs (coarse and fine) prepared using different drying techniques: hot air (HA), microwave (MW), and superheated steam (SS) at 110, 120, and 130°C

Size	**Drying treatment**	**Cooking losses % ± SD**	**Size**	**Drying treatment**	**Cooking losses % ± SD**
Coarse	HA	2.04 ± 0.13^{a}	Fine	HA	2.82 ± 0.04^{a}
	MW	2.11 ± 0.14^{a}		MW	2.21 ± 0.11^{b}
	SS 110°C	2.02 ± 0.07^{a}		SS 110°C	2.32 ± 0.13^{b}
	SS 120°C	1.88 ± 0.14^{a}		SS 120°C	2.37 ± 0.03^{a}
	SS 130°C	2.33 ± 0.23^{a}		SS 130°C	2.39 ± 0.20^{a}

[a-b] Values with different superscripts within the same column are significantly different (Tukey's HSD $p < 0.05$), sorted by drying treatment.