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Pre-harvest glyphosate application effects on properties of β-glucan from oat groats

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ABSTRACT

Pre-harvest glyphosate is applied to cereal grains to control weed growth. However, it has been claimed that oat *(Avena sativa* L.*)* composition is affected by pre-harvest glyphosate application. The research was conducted to evaluate differences in properties of β-glucan in grains of pre-harvest glyphosate treated versus untreated oat plants. Two oat cultivars (Rockford and Souris) were grown at Minot and Prosper, ND, in 2015, and glyphosate was sprayed during the soft dough stage, hard dough stage, or not applied. β-glucan viscosity was not significantly ($p > 0.05$) affected by treatment at soft dough (1082 cP) or mature (1166 cP) stages compared with untreated (1150 cP) controls. Applying glyphosate at the soft dough stage significantly ($p < 0.05$) reduced the content and solubility of the β-glucan versus untreated samples. β-glucan content and solubility in oat treated at soft dough were 4.35% and 52.1%, respectively, while in untreated samples were 4.65% and 60.6%, respectively. Treatment at soft dough and hard dough stages significantly ($p < 0.05$) increased weight average molecular weight (M_w) of the high molecular weight fraction of soluble β-glucan (4.4×10^6 and 3.8×10^6, respectively), compared with untreated controls (3.5×10^6). The M_w of the low molecular weight fraction of soluble β-glucan fraction significantly ($p < 0.05$) increased at soft and hard dough treatments (5.5×10^5 and 3.3×10^5, respectively), versus untreated samples (3.0×10^5). Therefore, glyphosate can be applied when the grain has reached physiological maturity or thereafter.

1. Introduction

Products made from oat groats are highly recommended for human consumption because they are a good source of dietary fiber, most of which consist of β-glucan (Gulvady et al., 2013). β-glucan is an unbranched polysaccharide component of the endosperm and aleurone layers of oat groat (Wood, 2011). Oat β-glucan structure consists of linear unbranched β-(1 → 4) linkages in groups of two to four units, which are separated by one β-(1 → 3) linked glucose unit. Because of successive β-(1 → 4), linkages in blocks separated by a β-(1 → 3) linked glucose unit, β-glucans form viscous solutions. The chemical structure of β-glucan is responsible and contributes to the properties of β-glucan, including solubility and viscosity (Cui and Liu, 2013). Another factor influencing the solubility of β-glucan is the molecular weight. β-glucan consists of up to 200,000 glucose units, resulting in a high range of average molecular weight (Kala et al., 2013). Molecular weight and chemical structure are two main factors that determine the solubility of β-glucan (Wang and Cui, 2005). Molecular weight is an important characteristic of oat β-glucan, as the molecular weight is related to physiological function for human's health. An increase in the molecular weight of β-glucan leads to a decrease in its solubility due to the rise in cohesive energy density. However, the β-glucan structure promotes its solubility, leading to health benefits. A set of (1 → 3) and (1 → 4) linkages in β-glucan disturb intermolecular hydrogen bonding, resulting in a water-soluble fiber molecule (Johansson et al., 2007). Oat β-glucan is more soluble and viscous than other fibers such as cellulose because of β-(1 → 3) linkages, which provide unique physiochemical features in health promotion (Cui and Liu, 2013).

Viscosity is the key physiochemical feature associated with the physiological influences of oat β-glucan. Attenuation of postprandial blood glucose and lowering of low-density lipoprotein (LDL) cholesterol levels are primarily attributed to the β-glucan's ability to increase viscosity (Gamel et al., 2012). The ability of β-glucan to generate high viscosity depends mainly on concentration, molecular weight, and solubility of the fiber (Wang et al., 2016). To many consumers β-glucan, a large part of the dietary fiber found in oatmeal is an essential factor as to why oatmeal has become a popular food item due to the benefits of lowering cholesterol levels and controlling blood glucose response. It is

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Table 1
Physical quality and β-glucan content of oats treated with glyphosate.

Glyphosate Treatments	Plump (%)	Groats (%)	β-Glucan Content (%, DWB)
Untreated	92.32a	70.28a	4.65a
Soft Dough	90.56b	68.90b	4.35b
Hard Dough	92.68a	70.00a	4.43b

n = 36, Values are means of all locations/cultivars. Values in the same column with the same letter are not significantly different ($p > 0.05$). DWB: dry weight basis.

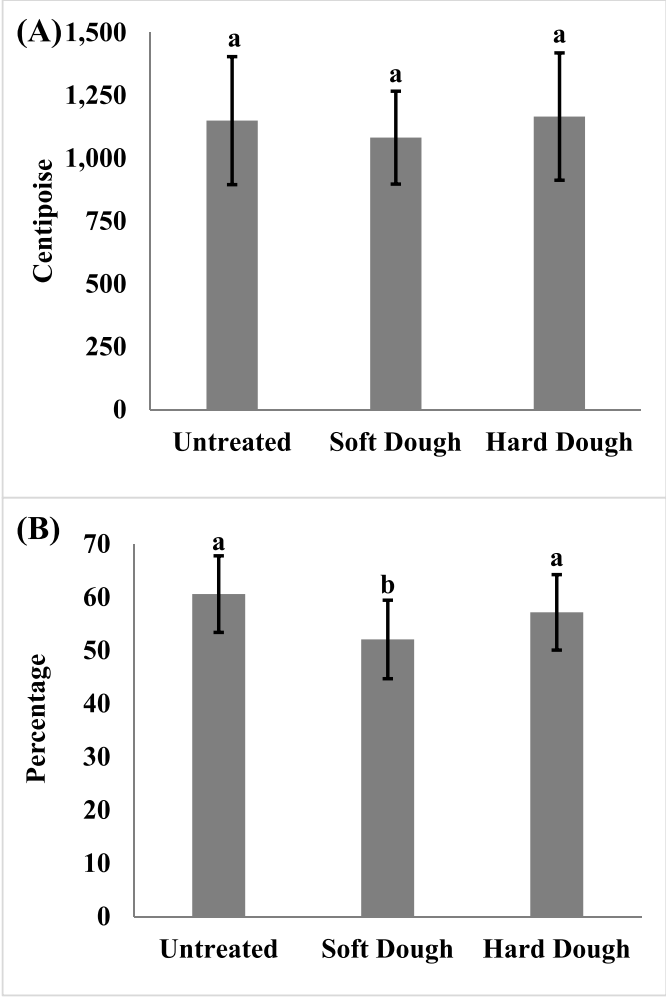

Fig. 1. Viscosity of β-glucan from oat groats (A), and solubility of β-glucan of oat groats (B) treated with glyphosate. n = 36, Values are means of all locations/cultivars. Error bars represent standard deviation. Columns in the same graph with the same letter are not significantly different ($p > 0.05$).

accepted that for every 1% reduction in LDL cholesterol levels, the risk of coronary heart disease is lowered by 1–2% (Wood, 2011). Ingesting oat β-glucan is beneficial for healthy people and patients who have Type 2 diabetes as well (Wood, 2011).

Glyphosate (*N-phosphonomethyl glycine*) is considered a broad-spectrum herbicide, which provides control of annual and perennial weeds. Glyphosate is an enzyme inhibitor that stops the activity of the enzyme 5-enolpyruvyl shikimate-3-phosphate synthase (EPSPS). This enzyme is naturally produced and utilized to synthesize proteins needed for plant growth (Dill et al., 2010). Inactivation of this enzyme inhibits the formation of aromatic amino acids, such as tyrosine, which leads to plant death. Additionally, inhibition of enzyme EPSPS leads to an uncontrolled flow of carbon into the shikimate pathway, resulting in the deregulation of carbon fixation and accumulation of shikimic acid in the grain (Malalgoda et al., 2020a). Since the enzyme EPSPS is not present in humans and animals, glyphosate is not listed as a biological hazard for humans. Thus, glyphosate is classified as non-poisonous to mammals, with an LD_{50} greater than 5 g kg^{-1} for rats (Annett et al., 2014). However, glyphosate is a non-selective herbicide because the enzyme EPSPS is conserved and activated on a wide range of plant species. Hence, some studies suggest that glyphosate use may contribute to environmental toxicity, such as residues persisting in soils (Bai and Ogbourne, 2016).

In addition to weed control, glyphosate may be applied to cereal crops just prior to harvest. Applying glyphosate before harvest will desiccate weeds, which will also reduce moisture content and speed up the harvest (Manthey et al., 2004). Typically, glyphosate can be sprayed on crops when a grain reaches physiological maturity, and the kernel is at the hard dough stage. However, the crops cannot legally be treated with glyphosate at soft dough stage (Griffin et al., 2010; Monsanto Company, 2017; Stebbins, 2018). Treatment of glyphosate at different harvest stages may impact grain quality and composition. This has been previously studied in wheat grain (Malalgoda et al., 2020a, 2020c, 2020b; Malalgoda et al., 2019), but additional study is needed for glyphosate application on oats.

Consumer hesitation concerning food ingredients and compositions is growing, especially over the use of pesticides on foods (McHughen, 2013). Since pre-harvest glyphosate application allows for a more convenient harvest, it is worth examining whether this practice does, in fact, impact oat β-glucan properties. Due to the health benefits of oat β-glucan and an increase of glyphosate application on cereal crops, it is important to analyze β-glucan concentration, viscosity, solubility, and molecular weight to ensure glyphosate does not adversely affect health benefits of β-glucan. The aim of this study was to determine the total β-glucan production in oat groats treated with pre-harvest glyphosate versus untreated oat groats. Importantly, the research was conducted to evaluate differences in the properties of β-glucan in the treated versus untreated oat groats.

2. Materials and methods

2.1. Materials

Oat grains utilized in the research were grown during the 2015 crop year at two locations: Prosper, ND, and Minot, ND, the United States of America. Eighteen samples were cultivated in Prosper and consisted of the cultivars, Souris, and Rockford. Each cultivar from Prosper received three treatments of glyphosate: untreated check, soft dough, and hard dough (physiological maturity). Each of the treatments included three replications. Another 18 oat samples were harvested in Minot and consisted of the same treatments and replications that were used in Prosper. Glyphosate was applied in the form of Monsanto's Roundup PowerMAX® Herbicide, Registration No. 524–549 at a concentration of 866 g glyphosate acid/ha. Therefore, 36 samples in total were collected by the Plant Sciences Department, North Dakota State University (Fargo, ND, USA).

2.2. Oat processing

All samples were first cleaned using a dockage tester made from Carter-Day International Company, Minneapolis, MN. The plump oats were then used for the dehulling process. The groats were separated from the hulls by Codema Laboratory Oat Huller. Each of the oat grain samples was dehulled using an air-pressure dehuller to remove the hull from the grain resulting in two portions: the hulls and the groats (Decker et al., 2014). In addition, the groats with some hulls left were placed into the grain aspirator machine. The freshly dehulled raw oat groats were steamed and kilned, and then ground.

The heat was applied in order to inactivate enzymes such as lipase,

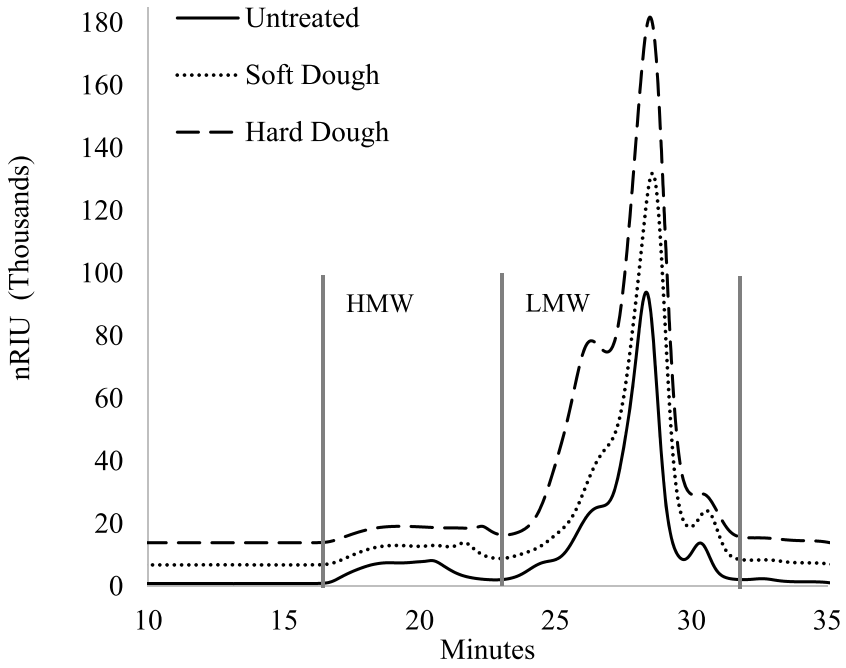

Fig. 2. Chromatograms of β-glucan from oat groats treated with glyphosate. HMW = High molecular weight fraction, LMW = Low molecular weight fraction.

lipoxygenase, and β-glucanases, which affect the physicochemical properties of oat and oat β-glucan during oat processing (Ovando--Martínez et al., 2013). To apply heat, 100g of oat groats were placed in a mesh basket and steamed at 100% humidity, at 100 °C for 40 min using an Adcraft full-size food cooker/warmer 1500W (Admiral Craft, Westbury, NY). During steaming, the basket of groats was stirred via a small stirrer every 10 min to prevent the groats from sticking to the basket. The mesh basket was held in the Adcraft warmer while stirring to maintain even temperature. The temperature was monitored by a probe thermometer.

After steaming, the oat groats were immediately kilned at 106 °C for two hours in a convection oven (Ovando-Martínez et al., 2013). The groat samples were kilned in the convection oven, stirring the samples every 20 min to prevent the groats from sticking inside the basket. The mesh baskets were held in the oven during stirring to maintain even temperature. Afterward, the groats were removed from the oven and left out to cool and dry overnight at room temperature to allow the moisture to equilibrate. Then, the oat groats were ground using an Udy Mill to produce oat flour. The 25-g samples of the steamed and kilned groats were milled in the Udy Mill fitted with a 0.5 mm sieve.

2.3. Rheological measurements of oat β-glucan

Determination of β-glucan viscosity in oat flour was completed using an *in vitro* digestion protocol that included incubating samples with enzymes to hydrolyze the starch and protein components of the oat flour (Beer et al., 1997). Rapid Visco Analyzer (RVA) was used to perform the analysis of the heat-treated groat samples. The weights of flour sample and buffer in grams were determined depending on the β-glucan content and moisture content of each sample. To produce a 1% β-glucan slurry, oat flour ranging from five to seven g (based on β-glucan content of the sample) was weighed into an RVA canister. The buffer (20 mM sodium phosphate and 10 mM sodium chloride with pH 6.9) was poured into the RVA canister (25 mL at 14% moisture basis). The enzymes added to hydrolyze protein and starch were chosen to mimic human digestion in the laboratory. Three digestive enzymes were placed to the RVA canister in the following amounts: 63 μL of salivary amylase (220 U/mL in 2.5 mM $CaCl_2$), 150 μL of pepsin (1150 U/mL in 0.9% NaCl), and 300 μL of pancreatin (0.5 mg/mL in sodium phosphate buffer, pH 6.9). All the contents of the RVA canister were well-mixed, and the canister was inserted into RVA for analysis of the viscosity of β-glucan. The RVA test launched with constant mixing speed at 480 rpm for 10 s, followed by reduction to 160 rpm and stirring for 2 h at 37 °C (Wang et al., 2016). After 2 h, the canister was removed from the RVA, and the final viscosity represented β-glucan viscosity.

2.4. Solubility of oat β-glucan

The amount of oat β-glucan solubilized by the enzyme treatement in the RVA was determined. First soluble β-glucan was separated by centrifugation. Homogenous aliquots of the slurry from the RVA canister was centrifuged at 13,000×*g* for 15 min. The amount of β-glucan in the supernatant was considered to be the soluble β-glucan, and the supernatant was removed and placed into tubes, and it was frozen for determination of soluble β-glucan. The frozen supernatant that came from the centrifuge of slurry of RVA canister was thawed. After thawing, 0.5g thawed sample was weighed into a clean screw cap type test tube. Then, the amount of soluble β-glucan was determined with a Megazyme kit, AACCI approved method 32–23.01 (Cereals and Grains Association, 2009). The percent β-glucan solubility was calculated as the ratio of soluble β-glucan to total β-glucan.

2.5. Molecular weight of soluble β-glucan

Homogenous aliquots of the slurry derived from the RVA canister was centrifuged at 13,000×*g* for 15 min to obtain a supernatant. The supernatant was boiled, cooled, and frozen. To prepare for measuring molecular weight, 150 mM sodium nitrate with 0.02% sodium azide buffer (pH 8.0) was filtered through a 0.2 μm nylon syringe filter. After thawing supernatants, the samples (0.74–6.81 mg) were placed into screwcap test tubes depending upon the β-glucan concentration of each sample. Then, the samples and Shodex Standard P-800 Pullulan were dissolved by adding 1 mL 0.1um filtered buffer while they were gently vortexed and then heated at 90 °C for 3 h. Water (0.49–4.54 mL) was added to samples, and an extra 1.5 mL was placed to all samples to be diluted. The final β-glucan content for all samples was 1.5 mg/mL.

The samples were analyzed using an Agilent 1200 high-performance liquid chromatograph with a refractive index (RI) detector and a Wyatt

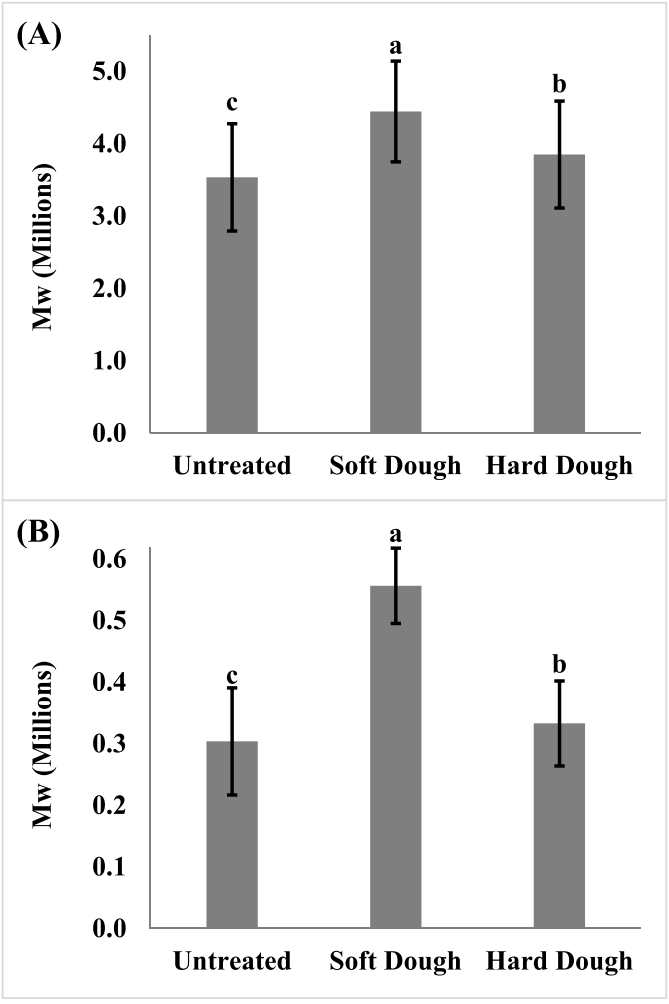

Fig. 3. Weight average molecular weight (M_w) of high (A) and low (B) molecular weight fractions of β-glucan from oat groats with glyphosate treatments. n = 36, M_w = Weight average molecular weight, Values are means of all locations/cultivars. Error bars represent standard deviation. Columns in the same graph with the same letter are not significantly different ($p > 0.05$).

Technologies multi-angle laser light scattering (MALS). The injection volume was 50 μL and a Shodex Ohpak SB-806M column, which was held at 25 °C and was used for separation. 150 mM sodium nitrate containing 0.02% sodium azide was used as an eluant, and the flow rate of the mobile phase was 0.4 mL/min (Storsley et al., 2003; Wang et al., 2016). The calculation of molecular weight was completed using Astra software v. 6.0.5, and the d*n*/d*c* value was 0.145 for β-glucans (Storsley et al., 2003). Normalization was conducted using a pullulan standard with a known molecular weight. The weight average molecule weight (M_W) was quantified using a Debye plot with a fit degree of 2 and a first-order polynomial fit.

2.6. Statistical analysis

This experiment was designed using a split-plot layout, with the location as the main plot and cultivar and glyphosate application as the sub-plots. Statistical analysis was performed with Statistical Analysis Software (SAS for Windows 9.4, SAS Institute, Cary, NC). The least significant difference (*p*-value) was used for mean separation.

3. Results and discussions

3.1. Physical quality of oat groats

Physical quality of oat groats is important for oat processing. The physical quality of the oats was impacted by growing location (data not shown), which is to be expected due to differences in soil condisitons and weather (Alahmed, 2019). Greater percentages of plump oats result in a higher percentage of groats, which meet the quality requirements for milling (Decker et al., 2014). Groat percentage refers to the amount of hull-less grains acquired after dehulling. High groat percentage is a good marker of milling yield in oats. The results from the cleaning experiment showed a general change that plump oat percentages ranged from 90.56 to 92.68% for the 2015 crop year. Significant ($p < 0.05$) differences in plump grains were found among the glyphosate treatments (Table 1). Treatment at the soft dough stage led to a significantly ($p < 0.05$) lower percentage of plump oats, 90.56% versus untreated samples with 92.32% plump. This is potentially because the oats treated at the soft dough stage did not completely mature or develop, resulting in smaller grains. The application of glyphosate creates a disruption of the shikimic acid pathway leading to high carbon outflow in the pathway. Thus, glyphosate application during seed development with less carbon available can reduce seed production, resulting in smaller oat grains (Griffin et al., 2010).

The findings from the dehulling experiment demonstrated that groat percentages ranged from 68.90% for soft dough treatment to 70.28% for untreated controls. Groat percentage was significantly ($p < 0.05$) lower in the soft dough treatment oats compared with other treatment samples (Table 1). Similarly, the groats treated at the soft dough stage did not entirely mature or develop (by contrast, the treatment at hard dough stage), resulting in smaller groats. The application of glyphosate during seed development might result in a lower production of seed, leading to smaller groats. Early glyphosate application led to a lower groat percentage because the groat was smaller, which led to a higher hull proportion being in the kernel weight.

Glyphosate applied at the soft dough stage reduced the percentage of plump grains and groat percentage when compared with the untreated samples. However, the plump grains and groat percentages were not significantly affected at the hard dough stage as it is possible that the oat kernels were fully developed before glyphosate killed or affected the grown oat plants. The lower percentage of plump oats results in a lower groat percentage, which decreases the milling quality of oats. Consequently, the pre-harvest application of glyphosate at the hard dough stage did not have negative effects on the physical quality of oat groats.

3.2. β-Glucan content

The samples showed some changes in the physicochemical properties of β-glucan due to glyphosate treatment, as well as growing location (Alahmed, 2019). β-glucan content for the three treatments ranged from 4.35 to 4.65%. This measurement is within the range reported by other studies without the use of glyphosate, which indicated the β-glucan contents to be approximately 3–5% in oat groats (Anttila et al., 2004). The concentrations of β-glucan from oats treated at both stages, soft dough, and hard dough, had significantly ($p < 0.05$) lower contents compared with untreated oat groats with 4.65% β-glucan. The lowest concentration of β-glucan was in samples that were treated at the soft dough stage (Table 1). Lower β-glucan concentration is indicative of a decrease in viscosity, solubility, and molecular weight of the fiber, leading to reducing its health benefits (Mitra et al., 2017).

Also, the maximum amount of β-glucan is reached after the soft dough stage when seed growth is almost completed. Hence, the glyphosate application during the soft dough stage might affect the maximization of β-glucan concentration. The reduction of β-glucan content by glyphosate treatment, especially at the soft dough stage, may cause a significant change in the nutritional value of oat products.

3.3. Viscosity of β-Glucan

The differences in β-glucan viscosity were not statistically significant ($p > 0.05$) among the untreated samples and oats treated at soft dough and hard dough stages. There was an effect of cultivar and growing location on β-glucan viscosity (Alahmed, 2019). Even though the β-glucan viscosity was not significantly ($p < 0.05$) different, a higher viscosity of the fiber was observed in oats treated at the hard dough stage by 1165.75 cP compared with the untreated samples 1149.67 cP. The viscosity for soft dough-treated oats was 1082.17 cP, which was lower than the viscosity of β-glucan in the untreated controls but was not significantly ($p < 0.05$) different (Fig. 1A).

The reason for the decrease of viscosity of β-glucan from the soft dough treatment samples could be because of the low concentration of β-glucan at this treatment. The β-glucan content of the groats treated at the soft dough stage had about 0.3% less β-glucan than the untreated oats. This small reduction in β-glucan content may have impacted the small, but non significant ($p < 0.05$) reduction in β-glucan viscosity. The higher concentration of β-glucan creates a higher viscosity required for the health benefits such as attenuating postprandial blood glucose and lowering LDL cholesterol levels (Gamel et al., 2012). Glyphosate application possibly interferes with the grain filling period that occurs in the soft dough stage, leading to a smaller β-glucan content, resulting in a lower β-glucan viscosity. In contrast, a reason for the increase in β-glucan viscosity among the three treatments, especially in untreated and hard dough stage samples, is due to heat processing, which is due to the inactivation of endo-β-glucanase (Liu et al., 2010). High viscosities of some samples from both cultivars are related to no active endo-β-glucanase within 2 h kilning and 40 min steaming. In addition, polysaccharide components, such as starch, have an effect on oat viscosity (Anttila et al., 2004). It has been determined that the application of glyphosate has an effect on starch content (Malalgoda et al., 2020c; Stebbins, 2018), which was not investigated in this study.

3.4. Solubility of β-Glucan

The oats treated with glyphosate at the soft dough stage had significantly ($p < 0.05$) lower β-glucan solubility than either untreated groats or groats treated with glyphosate at the hard dough stage (Fig. 1B). The percent β-glucan solubility was 60.59, 52.08, and 57.17% for untreated, treated at soft dough, and treated at hard dough oats, respectively. Though the oats treated with glyphosate at the hard dough stage had lower β-glucan solubility than untreated oats, the difference was not significant ($p < 0.05$). The solubility of β-glucan was significantly ($p < 0.05$) effected by location and cultivar (Alahmed, 2019).

High β-glucan content in oat groats is potentially a factor causing an increase in its solubility. Thus, a low quantity of β-glucan led to less solubility of β-glucan, which reduces the health benefits of oat consumption. Oats with high concentrations of β-glucan tend to include more soluble β-glucan located in the groats (Wang et al., 2016). In this study, higher β-glucan concentration appeared to be related to higher β-glucan solubility, independent of its molecular weight. Soft dough-treated groats negatively affected the concentration and solubility of β-glucan. Physiological maturity treatments did not have a meaningful influence on oat β-glucan concentration and solubility. Presumably, application at the hard dough stage is a prime time in the grain growth that glyphosate might not interfere with the grain filling, or other component development that may affect β-glucan solubility.

3.5. β-Glucan molecular weight

The weight average molecular weight (M_w) of oat β-glucan was determined from the light scattering intensity of samples separated by HPSEC. The chromatograms of the β-glucan from oats treated with glyphosate are shown in Fig. 2. There were two fractions of soluble β-glucan: high molecular weight (HMW) fraction and low molecular weight (LMW) fraction. All oat samples contained a greater proportion of LMW fraction in the soluble β-glucan.

The M_w of the HMW and LMW fractions of soluble β-glucan extracted from oats treated with glyphosate are shown in Fig. 3a. The M_w of the HMW fraction of β-glucan differed significantly ($p < 0.05$) among treatments. The M_w of the HMW fraction of soluble β-glucan was 3.54×10^6, 4.44×10^6, and 3.85×10^6, for untreated, soft dough treated, and hard dough treated oats, respectively. The M_w of the LMW fraction of soluble β-glucan was 0.30×10^6, 0.56×10^6, and 0.33×10^6, for untreated, soft dough treated, and hard dough treated oats, respectively.

The differences in HMW and LMW fractions of the soluble β-glucan seemed to imply that lower solubility of β-glucan was associated with their higher molecular weights (Fig. 3A and B). These results support the concept that β-glucan having higher molecular weight will have lower solubilization (Grundy et al., 2017). Glyphosate applications indirectly affected HMW and LMW fractions of the soluble β-glucan by reducing the solubility of the oat β-glucan. Increased solubility of β-glucan is a desirable property in oat-based foods, resulting in enhanced physiological activities. The high molecular weight of β-glucan provides more health benefits compared with low molecular weight forms of the fiber, as long as the solubility is not reduced. Also, molecular weights of oat β-glucan with the soft and hard dough treatments of pre-harvest glyphosate application might be related to the inactivation of endo-β-glucanase during steaming and kilning (Wang et al., 2016). The solubility significantly decreased at the soft dough stage because the molecular weights of β-glucan significantly increased.

Molecular weight of β-glucan is often associated with increased viscosity (Mitra et al., 2017). However, the results of this study did not show increased viscosity for the oat groats treat at the soft dough stage. The changes in β-glucan solubility and reduced β-glucan content of the oat groats in this study could be impacting the viscosity and resulting in the increased β-glucan molecular weight having less effect on viscosity.

Physicochemical characteristics of β-glucan can be evaluated to understand the health benefits of oat products better. For instance, higher oat β-glucan content is indicative of elevated β-glucan viscosity and higher molecular weight of the fiber (Kim and White, 2013). In addition, higher soluble β-glucan indicates an improved viscosity of β-glucan, while higher β-glucan solubility leads to the lower molecular weight of the molecule. β-glucan is a viscous fiber based on its content, and its solubility is based on its molecular weight. The higher viscous and greater soluble β-glucans found in oats are associated with two major health-promoting effects the attenuation of postprandial blood glucose and the control of LDL cholesterol levels (Kala et al., 2013).

4. Conclusion

The application of glyphosate at the soft dough stage had an impact on the physicochemical characteristics of β-glucan in oats. The use of glyphosate at the soft dough stage decreased the percentage of β-glucan concentration, which is possibly due to interruption of β-glucan production in the oats or changes in composition due to reduced plumpness. Pre-harvest glyphosate during the soft dough stage resulted in low solubility and low viscosity of oat β-glucan. The application of glyphosate at the soft dough stage reduced the β-glucan solubility and increased its molecular weight compared with the untreated controls. Pre-harvest glyphosate at the soft dough stage significantly affected β-glucan content, solubility, and molecular weights, while treatment at the hard dough stage only affected β-glucan concentration and its molecular weights. Early pre-harvest application of glyphosate can influence the development of β-glucan in oat groats. Therefore, to maintain viscosity and solubility of oat β-glucan, it is recommended farmers apply glyphosate at the low moisture stage (hard dough) or thereafter. Future research can be performed to determine the cause of the decrease in physiochemical properties of the β-glucan observed, especially in groats treated at the soft dough stage. Sensory evaluation of end-use products can be a future study to ensure pre-harvest glyphosate does not

adversely affect sensory properties, such as flavor, of oat productions. Also, this study had a limited scope, testing two cultivars for one year. A multi year study should be done on several oat cultivars at several growing locations to confirm the findings of this study.

CRediT authorship contribution statement

Abdulrahman Alahmed: Investigation, Methodology, Writing - original draft. **Senay Simsek:** Conceptualization, Data curation, Supervision, Writing - review & editing.

Declaration of competing interest

None.

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