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Multi-use naked barley: A new frontier

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ABSTRACT

Barley (*Hordeum vulgare*) is one of the oldest known domesticated crops and the fourth most widely grown cereal crop in the world. Barley has three principal end-uses: feed, food, and malt. Each end-use of barley requires different characteristics, but hull adherence and beta-glucan content are important for each of the three classes. Naked (hull-less) barley, which threshes freely from the hull, makes up a very small percentage of overall barley production and is mainly grown for food end-uses. However, naked barley shows potential as a crop that can be used for multiple end-uses. This review will describe the progression of naked barley in the US as well as ongoing research at Oregon State University. With the genetic resources from around the world that are available in germplasm repositories and continued research on end-use quality, advances can be made to create a new frontier of naked barley for multiple end-uses that will benefit growers, processors, and consumers.

1. Introduction

Barley (*Hordeum vulgare*) is one of the oldest known domesticated crops and the fourth most widely grown cereal crop in the world (FAOSTAT, 2019). Barley is a versatile crop with three principal end-uses: feed, food, and malt. In 2019, 51M hectares were harvested globally to produce a total of 159M tonnes; in the United States, 0.9M hectares were harvested to produce 3.7M tonnes (FAOSTAT, 2019). Although there are no statistics available, it is safe to assume that the overwhelming majority of this is covered (hulled) barley with an adhering husk. Feed barley and malting barley, which account for the majority of production are predominantly covered types. Naked (hull-less) barley, which threshes freely from the hull, makes up a very small percentage of overall barley production and is mainly grown for food end-uses. Although there are areas of the world where barley is consumed widely, barley grown for food in the United States only accounts for 4% of total barley production (AMBA, 2020). Because a portion of the food barley produced is a covered type that has been pearled (a physical abrasion process to remove the hull), naked barley accounts for <4% or fewer than 35,000 ha of production in the US- the exact area is unknown due to the minority status of the crop.

Given the changing climate, where complete crop failure or more minor yield and quality reductions will become an annual reality, breeding new varieties for growers that can be sold into a range of markets became a target of the Oregon State University (OSU) program. Because the decision had already been made to focus on breeding whole grain naked food barley and naked feed barley can be beneficial for non-ruminants, researchers chose to target breeding naked barley for multiple end-uses, including food, feed, and malt. Meints and Hayes (2019) have previously published a review on the topic; this paper will describe the progression of naked barley in the US as well as ongoing research at Oregon State University.

2. A history of naked barley in the US

There are several reasons for the current state of naked barley production in the United States. The first is that barley is a relatively minor food crop compared to other cereals. The lack of functional gluten as compared to wheat for baking and the predominance of oats for flaking and rice as a cooked grain have left barley in the dust as an ingredient in most consumers' pantries. For malting, which is the major end-use in the US at 67% of production, none of the American Malting Barley Association (AMBA) recommended varieties are naked. Feed barley production in the US has declined (currently 27% of total production) as cheaper feed sources have dominated the market (Blake et al., 2010), and a portion of the barley that moves into the feed industry is covered malting barley that didn't meet the quality requirements. Another reason for the lack of naked barley production is that as a result of the market stratification, barley breeders in the US have focused their efforts on releasing covered varieties over the last century. Several breeding programs have devoted a small portion of their research to developing naked varieties for the food market, but over the last 100 years, only 22 naked barley varieties developed in the US have been entered into the

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Abbreviations

AMBA	American Malting Barley Association
DE	Digestible Energy
DON	Deoxynivalenol
ERF	Ethylene Response Factor
FAN	Free Amino Nitrogen
GBBSI	Granule-bound Starch Synthase I
GWAS	Genome Wide Association Studies
OSU	Oregon State University
QTL	Quantitative Trait Locus
RDF	Real Degree of Fermentation
SNP	Single Nucleotide Polymorphism
USDA-GRIN	United States Department of Agriculture, Germplasm Resources Information Network

United States Department of Agriculture, Germplasm Resources Information Network (USDA-GRIN) system at the National Small Grains Germplasm Collection in Aberdeen, ID (Table 1).

In order to get an idea of the current naked barley germplasm that exists around the world, all barley accessions that have been entered into this germplasm repository were sorted based on hull adhesion. Out of the 36,734 barley lines entered into GRIN, 3003 are classified as "hulless" (naked). While this does not account for nearly all of the naked germplasm that exists globally, it provides a snapshot of how naked barley is distributed around the world. Compared to the global production share of barley from 1994 to 2019 as reported by FAOSTAT (2019) (Fig. 1), the distribution of naked barley looks very different (Fig. 2). Whereas most of the world's barley is produced in Europe, a relatively small percentage of the naked barley in GRIN was collected in Europe. Asia represents the region with the most naked barley accessions, which were primarily collected in China, Japan, Nepal, and India. Additionally, the percentage of naked barley originating from Africa represents a much larger percentage compared to overall production. Barley is an important food crop in these areas of the world, particularly the Himalayan and Andean regions, Japan, Ethiopia, and Morocco, which explains the greater numbers and more diverse germplasm collected from these countries (Grando and Gomez Macpherson, 2005). From the United States, 124 naked barley lines have been entered into GRIN, with 22 released as varieties (Table 1). The earliest lines (improvement status designated as 'uncertain') were collected in the early 1900s, and were imports from other countries ('Nepal' in 1904, 'Himalaya' in 1918, 'Purple Nepal' in 1919, and 'Tibetan' in 1919) (Michels, 1936). This germplasm is found in the pedigrees of the early varieties developed in the United States. Although there is little documentation on the earliest varieties, it is likely that these were developed for food end-uses, which is the primary end-use of almost all naked barley varieties developed in the US, with only a handful being bred for feed or biofuel end-uses. In the US there have been no naked barley varieties released with a primary end-use of malt.

Although the earliest entered varieties are poorly described, several of the lines (7 of 22) were bred during the last 35 years for the food market and have waxy starch with higher than normal and/or high levels of beta-glucan. If naked barley production has increased in the last few decades, it is a result of dedicated research and human nutrition studies on beta-glucan. However, these waxy starch, high beta-glucan varieties have been developed for a food system that favors processed health foods, rather than whole grain diets, and the beta-glucan is extracted from the barley and added to functional foods (Goudar et al., 2020). While this process may appeal to the mass consumer, after conducting preliminary agronomic and food quality research on a small panel of winter food breeding lines, the Oregon State University (OSU) barley breeding program has chosen to focus on breeding varieties for whole grain baking and cooking (Meints et al., 2015a). From this panel, two winter naked barley lines with normal starch were released, #STRKR (a germplasm) and 'Buck' (a variety) (Meints et al., 2015b, 2018).

3. Multi-use naked barley

Currently, end-use in barley is determined by several factors. Malt barley bred for brewing or distilling must meet a number of specifications to be considered a high-quality variety, including protein content, percentage of plump kernels, and almost always an adhering hull. Post-malting, lines must exhibit certain levels of malt extract, free amino nitrogen (FAN), wort beta-glucan, alpha-amylase and several other traits to perform well in the brewing and distilling process (AMBA 2020). Food barley is poorly defined in the US; however, protein content, grain beta-glucan, starch type, and kernel hardness can affect the functionality of the grain in baked or cooked products. However, of these traits, breeders most often target naked lines with high levels of beta-glucan and/or waxy starch type (Meints and Hayes, 2019). Often barley

Table 1
Naked Barley varieties originating in the US entered into the USDA-GRIN germplasm repository. USDA-GRIN (2021).

Accession	Name	Origin	Received	End-use	Row type	Growth habit
CIho 4579	'Faust'	Montana	1925	Unknown	Six	Spring
CIho 5108	'New Era'	South Dakota	1930	Unknown	Six	Spring
CIho 5109	'Burbank Hull-less'	California	1930	Unknown	Six	Spring
CIho 6030	'Trapmar'	Alaska	1934	Unknown	Six	Spring
CIho 10641	'Godiva'	Utah	1959	Unknown	Six	Spring
CIho 13887	'Jaybel'	Maryland	1969	Unknown	Six	Spring
PI 608763	'Washonupana'	Montana	1976	Food	Two	Spring
CIho 15843	'Belonee'	Montana	1980	Unknown	Six	Spring
PI 601510	'Westbred Waxbar'	Montana	1988	Food	Two	Spring
PI 538761	'Shonkin'	Montana	1990	Food	Two	Spring
PI 560053	'Azhul'	Arizona	1991	Food	Six	Spring
PI 562645	'Thual'	Alaska	1992	Unknown	Six	Spring
PI 586965	'Merlin'	Montana	1995	Food	Two	Spring
PI 614008	'Bear'	Washington	2000	Feed/food	Two	spring
PI 645477	'Tamalpais'	California	2007	Food	Six	Spring
PI 647080	'Clearwater'	Idaho	2007	Feed	Two	Spring
PI 660128	'Transit'	Idaho	2010	Food	Two	Spring
PI 659067	'Eve'	Virginia	2010	Feed/Biofuel	Six	Winter
PI 659066	'Dan'	Virginia	2011	Feed/Biofuel	Six	Winter
PI 665006	'Julie'	Idaho	2012	Food	Two	Spring
PI 674325	#STRKR	Oregon	2015	Food	Six	Winter
PI 682744	'Buck'	Oregon	2018	Food	Six	Winter

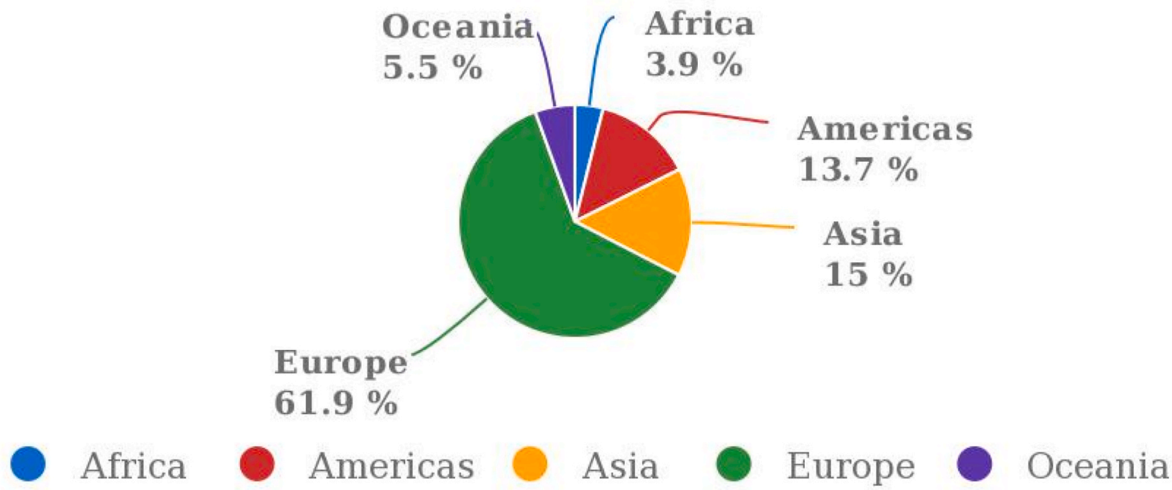

Fig. 1. Total production share of barley by world region including covered and naked barley. FAOSTAT (2019).

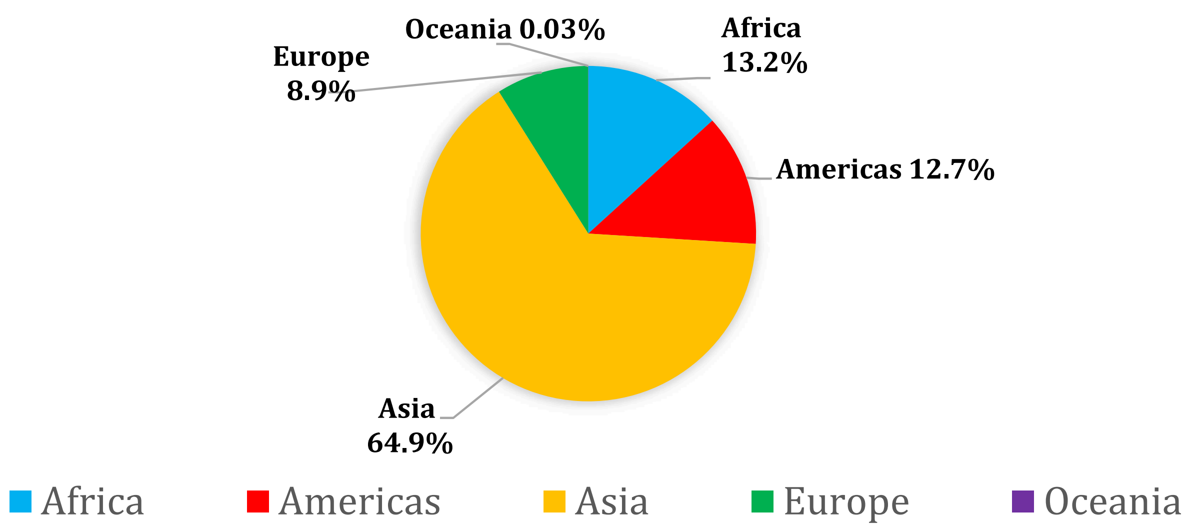

Fig. 2. Total naked barley accessions in USDA-GRIN by region of origin. USDA-GRIN (2021).

varieties that are grown for the feed market are lines that failed to meet malt specifications. However, breeding targets can include protein, digestible energy (DE), high starch levels, and low levels of non-starch polysaccharides (Rossnagel, 1999). Most feed types are bred with a hull, but occasionally naked types are selected for monogastric feed. The common traits that breeders target for all three end-uses include hull type and beta-glucan content. Malt barleys are nearly always covered and low beta-glucan; food barleys are typically naked with mid-high levels of beta-glucan; feed varieties can be either covered or naked with low beta-glucan levels.

Given the different end-use quality traits targeted in breeding work up until now, it is very unlikely that currently available varieties will perform well for all three end-uses. This means that growers have limited options for marketing their crop. Typically malt barley is grown on contract, but if it fails to meet spec, it is diverted into the feed market at a substantially lower price point (Baker et al., 2020). Food barley is also often grown on contract and depending on the variety may be able to be diverted to the feed market if the quality is poor. Due to climate change and increasingly unpredictable growing conditions, growers will benefit from varieties bred to have quality for multiple end-uses. A recent survey of organic barley growers in the United States showed that most would be interested in growing a multi-use naked barley (Baker et al., 2020). The OSU program has chosen to focus on breeding multi-use naked barley with moderate beta-glucan levels that growers can sell into the malt, food, or feed markets depending on post-harvest quality and price points. However, due to the lack of breeding effort put into breeding naked barley in the United States and the complexity of malt and food quality traits, this is not a simple task, but rather one that will take years of characterization and selection. The following sections describe traits of interest for breeding multi-use naked barley.

4. The *Nud* gene

Hull adherence is controlled by a single gene at the *Nud* locus on the long arm of chromosome 7H (Taketa et al., 2008). It is believed that the naked phenotype arose by spontaneous mutation approximately 2000 years after the domestication of barley (Yu et al., 2016). The *Nud* gene encodes an Ethylene Response Factor (ERF) family transcription factor (Taketa et al., 2008). In covered barley, the *Nud* allele results in production of a lipid based 'cement' secreted from the pericarp which causes the lemma and palea to adhere to the caryopsis (Swanston et al., 2011). Around 16 days after pollination, this cement begins to appear, but the pericarp and hull do not touch until grain filling (Newman and Newman, 2008). The *nud* allele prevents this from occurring, allowing the grain to thresh freely from the hull during harvest. *Nud* is an ortholog of *WIN1/SHN1* in Arabidopsis and it is believed that the function of this gene is to regulate a lipid biosynthesis pathway (Taketa et al., 2013). While the chemical composition of these lipids has not been fully characterized, they have been deemed integral in the adhesion of the caryopsis and hull (Taketa et al., 2013).

Consisting of two exons and one intron, the *Nud* gene codes for 227 amino acids (Taketa et al., 2013). There are currently two known natural mutations conferring the naked phenotype. The first is a 17-kb deletion at the *nud* locus (Taketa et al., 2008). This is the most common allele associated with the naked phenotype and is referred to as *nud* or *nud1.a* (Yu et al., 2016). The second is a single nucleotide polymorphism in the *Nud* gene. This SNP is a T to A substitution at position 643 with the resulting amino acid sequence having a conversion of Valine to Aspartic Acid at position 148 (Yu et al., 2016). This SNP results in a completely different allele than the primary *nud* allele and has been designated *nud1.g* (Taketa et al., 2008). Mutations induced via radiation methods have also led to the development of artificial alleles conferring the same naked phenotype; four of these five artificial alleles are SNPs within the *Nud* gene while one is a 1bp deletion causing a frameshift (Taketa et al., 2008, 2013).

The *nud* allele has not been found to have pleiotropic effects on agronomic traits such as grain yield, grain weight, plant height, or heading date (Barabaschi et al., 2012; Gerasimova et al., 2020). Gerasimova et al. (2020) used an RNA-guided Cas9 endonuclease to knock-out the *Nud* gene in the covered variety 'Golden Promise' to develop a naked isogenic line to further study pleiotropic effects of the *Nud* gene. A QTL relating to grain yield and thousand grain weight has been mapped to chromosome 7H near the *Nud* locus, but it is believed that this effect is most likely due to linkage (Barabaschi et al., 2012). This indicates that breeding efforts to improve yields in naked barley to the level of covered barley are possible. Currently, due to fewer breeding efforts for naked barley, yields are lower, which can be partially explained by the adhering hull on covered barley, which itself accounts for approximately 10–13% of the weight and volume of the harvested barley grain (Rey et al., 2009). Because the hull is made up primarily of cellulose, lignin, and silica; naked barley generally contains greater levels of protein, starch, and total and soluble beta-glucan than covered barley due to the dilution effect the hull has on these components (Meints and Hayes, 2019). It has been found that naked barley lines do have lower kernel weight and percent plump kernels than covered barley, which is a result of the lack of hull and therefore the *Nud* gene (Xue et al., 1997). Other traits related to the *Nud* gene have been reviewed in Meints and Hayes (2019).

5. Beta-glucan

Beta-glucan is a soluble dietary fiber found primarily in barley and oats (as reviewed in Meints and Hayes, 2019). Beta-glucan is naturally produced in barley, but higher levels can be achieved via chemically induced mutation (Newman and Newman, 2008). Beta-glucan accounts for approximately 2–10% of the dry mass of the kernel (Martin et al., 2018), and naked barley generally has higher starch and beta-glucan levels than covered barley because of the lack of hull (Yangcheng et al., 2016). Beta-glucan content is a quantitative trait with several associated QTLs; one QTL is located on chromosome 7H and is within 5 cM of the *Nud* gene (Swanston, 2014) indicating a possible linkage effect. It is known that there is a pleiotropic effect between beta-glucan and the recessive allele at the Waxy (*WX*) locus (Meints et al., 2015a). The Waxy gene codes for a granule-bound starch synthase I (*GBSSI*) (Li et al., 2021). Additionally, Li et al. (2021) performed a genome wide association study (GWAS) and found several new QTLs correlated with starch-related traits; these candidate genes and alleles can be used in future breeding work to specifically target amylose and amylopectin content. Additionally, mutations at the *Lys3* and *Lys5* loci can affect beta-glucan content, as well as other health-promoting compounds. These mutants have shrunken endosperms, but contain increased amounts of beta-glucans, fructans, arabinoxylans, and resistant starch (Christensen et al., 2012; Nakata et al., 2018). Lines with waxy starch have higher beta-glucan levels as well as reduced starch content compared to varieties with normal starch (Meints and Hayes, 2019; Fastnaught et al., 1996). Starch content is a determined by the relative levels of amylopectin to amylose in the grain and there are different starch types depending on concentrations: high amylose (35–45% amylose, 55–65% amylopectin), normal (25–30% amylose, 70–75% amylopectin), waxy (1–5% amylose, 95–99% amylopectin), and zero-amylose (100% amylopectin) (Yangcheng et al., 2016). While most barley varieties have normal starch, waxy types are more commonly found among naked barley lines due to the correlation between beta-glucan and dietary benefits (Li et al., 2021).

Depending on the intended end-use, beta-glucans can be favorable or problematic. Beta-glucan can be beneficial for food end-uses. Waxy starch barley also tends to have a more "uniform endosperm texture" making it a better product for some culinary applications (Meints and Hayes, 2019). As reviewed in Meints and Hayes (2019), there is a negative correlation between beta-glucans and malt extract levels, and beta-glucans can ultimately lead to lower quality beer. While the relationship between beta-glucan and malt quality has been relatively well characterized, the relationship between starch traits has not (Li et al., 2021). Future studies are necessary to fully determine the relationship between starch, beta-glucan, and malt quality.

The environment can also impact beta-glucan levels. Management practices such as increasing soil nitrogen can increase beta-glucan levels, while increased irrigation has shown to decrease beta-glucan content (Choi et al., 2020). Drier, hotter weather can also lead to increased beta-glucan levels while cooler, wetter conditions have generally shown decreased beta-glucan content (Meints et al., 2015a). A recent study by Martin et al. (2018) determined that varieties with higher levels of beta-glucan have shown lower levels of deoxynivalenol (DON), a mycotoxin that affects both humans and animals. In vitro, beta-glucan has been shown to bind to various *Fusarium* toxins (Yiannikouris et al., 2006). This trait can be potentially exploited for feed and food barley to reduce the risk and levels of infected grain (Martin et al., 2018).

6. Food quality

Barley can be processed into a number of different forms for human consumption. It can be milled into flour, ground into grits, rolled into flakes, or prepared as a whole grain (Bhatty, 1999). Because of the multitude of ways it can be processed, there are many different products that can be made from barley, including risen and flat breads, pastries and cookies, noodles and pasta, pancakes, tortillas, porridges, granola, whole grain salads, and fermented products including tempeh, miso, and shoyu (as reviewed by Meints et al., 2016). In the United States, food barley is consumed perhaps most notably in its pearled form in "beef and barley soup". At supermarkets in the US, the most common (and often only) option for barley is a generic pearled barley (Newman and Newman, 2008). In other areas of the world, barley has an important culinary history and culture and is prepared in many forms, including Tsangpa (also, spelled Tsampa, a roasted barley flour) in Tibet, as an ingredient in injera (a flatbread) in Ethiopia, couscous in Morocco, and as Machica or cracked barley in Ecuador (Grando and Gomez Macpherson, 2005). In the United States, barley is slowly being incorporated into more food products due to potential health benefits. Because of the barley's capacity to high levels of beta-glucan, a soluble dietary fiber, numerous clinical studies have been conducted demonstrating that beta-glucan can have many positive health benefits, including lowering post-prandial blood glucose levels, modulating gut microbiota (Tosh and Bordenave, 2020), and lowering of plasma LDL cholesterol concentrations (Joyce et al., 2019). These health benefits resulted in the approval of the FDA health claim for barley in 2006 (21CFR101.81) and similar claims in Europe (2011) and Canada (2012) (Ames and Rhymer, 2008). Despite the positive health benefits, beta-glucan and starch type impact the functionality and properties of grain processing and food products (Kinner et al., 2011; Meints et al., 2015a). Because of this, barley flour is infrequently included in commercially available bread products. Selecting for multi-use varieties with moderate levels of beta-glucan may result in a slightly less nutritionally-dense loaf, but one that may have better consumer acceptance (Kinner et al., 2011).

Recent research on whole-grain applications of food barley include several studies that incorporate naked barley into wheat sourdough breads. Previous studies have shown that incorporation of naked barley flour can reduce loaf volume and consumer acceptability when added to yeasted wheat breads, but because of the extended fermentation time of sourdough breads, the addition of naked barley flour doesn't have the same negative effects (Kinner et al., 2011). Pejcz et al. (2017), and Sterna et al. (2019) both demonstrated that adding barley flour or grains to wheat sourdough breads improved the bread nutritional quality, and that barley sourdough fermentation improved quality compared to wholemeal flour incorporation. Other research using up to 40% barley flour whole grain barley flour with moderate levels of β-glucan (4–5%), resulted in successfully risen sourdough loaves that received positive sensory reviews (Ross et al., 2017).

Naked barley is preferred for food end-uses because covered varieties must be pearled prior to human consumption to remove the unpalatable hull. This involves a mechanical abrasion process to remove the hull, which also removes part or all of the bran and germ, resulting in the grain being ineligible for whole grain status and losing valuable minerals and micronutrients that are located in the bran layer. Naked barley will occasionally be pearled if the threshability (ease of hull removal) is poor. Threshability is an important trait to select for in naked barley because end-use quality can decline if the percentage of grains with undetached hulls is over 5% for food and 15% for feed (Rossnagel, 1999). The genetic control of this trait is currently poorly defined, but new research conducted by the OSU breeding program and collaborators using GWAS to look at threshability on 384 naked barley lines grown at three locations over three years and two seasons, will help researchers better understand how many QTLs control the trait and aid in marker-assisted or genomic selection for the trait.

Due to the current lack of definition of quality traits in naked barley and the capacity for varieties to perform very differently in baking and cooking applications, bakers and chefs may be more hesitant to incorporate barley into recipes By measuring a host of grain quality and functionality traits researchers can develop a better lexicon for understanding how different innate characteristics can affect varietal performance in different applications. For example, water absorption capacity can predict how varieties may perform in risen breads, hardness can affect flaking quality, batter flow can affect performance in pancakes, and pasting viscosity and starch gel strength can impact the production of noodles (Ross et al., 2017).

7. Malt quality

In general, covered barley is used for malting because the hull protects the growing acrospires during the malting process and provides natural filtration during mashing. However, there has been growing interest in using naked varieties for malting, especially with the increased use of mash filters and centrifuges in the lautering step of brewing. Mash filters do not require the hull for filtration purposes during wort separation, making them a more ideal technology for naked barley (Krstanović et al., 2016). Naked barley can have potentially significant increases in malt extract due to the lack of hull (Li et al., 2006), as the hull accounts for 10–13% of the dry weight. It has also been shown that the hull can contribute to "off flavors" in the beer due to small hull particles fermenting (Bathgate, 2016). Tannins and polyphenols from the hull can also contribute to lower quality beer including unwanted haze formation (Edney and Rossnagel, 2000). Polysaccharides can also cause premature yeast flocculation during fermentation (Li et al., 2006). Naked barley has also shown to have less spent grain compared to its covered counterpart (Krstanović et al., 2016), making it more efficient during the brewing process which is a considerable incentive for brewers.

Since naked barley is relatively new to the malting world, not much breeding work has been done to develop varieties well-suited for malting. There are a number of issues that need to be addressed through breeding or cultural techniques to improve naked barley for this end-use. Naked types are more susceptible to embryo damage during harvest and malting, and in covered varieties the hull acts as protection for the embryo. Naked barley also tends to have a harder endosperm than covered barley (Bhatty, 1996). Kernel hardness is associated with beta-glucan content; low beta-glucan lines have thinner cell walls within the endosperm and therefore softer textures (Gamlath et al., 2008). Kernel hardness plays a role in water uptake during the steeping process. Gamlath et al. (2008) found a highly significant negative correlation between water absorption and kernel hardness, which affects modification and in turn leads to lower friability (Swanston, 2014) but is a quantitative trait not associated with the *Nud* gene, so directed breeding efforts for softer kernels in naked barley are possible, both with the use of breeding technology such as marker assisted selection (Meints and Hayes, 2019) and selecting for lower beta-glucan lines.

Because naked barley has mainly been bred for food or feed, many naked barley varieties have higher beta-glucan levels (Swanston, 2014). Beta-glucan can cause various issues in malting including haze and precipitates (Meints and Hayes, 2019). It has been shown that modified steeping and germination protocols can reduce un-degraded beta-glucans (Edney and Rossnagel, 2000). Preliminary data from OSU has found that a modified protocol consisting of 5 days of germination can dramatically decrease beta-glucan by ~200 mg/L (Table 2) in certain varieties. This is shown in Table 2, where the same variety, Buck, was malted with the same steeping and kilning protocol, but one batch was given 4 days of germination and the other was given 5 days of germination. The lots were grown in 2019 and 2020, respectively, in the Willamette Valley area in Oregon and had similar grain parameters, including grain protein content (Table 2). The difference in friability (70.6% with four days and 96.4% with five days) is also an important indicator of modification and is related to beta-glucan levels (Lewis and Young, 2004). With these preliminary data, it was determined that calibrating both the steeping and germination protocols is necessary and will ultimately lead to higher quality naked barley malt, regardless of wort separation equipment in the brewing process. The OSU barley breeding program is currently testing multiple different steeping and germination regimes to better understand the functionality and quality

Table 2
Malt quality of two different batches of Buck naked barley with the same malting protocol except for days of germination. Quality analysis measured at Hartwick College, Center for Craft Food and Beverage.

Parameters	Buck (4 days germination)	Buck (5 days germination)
Moisture (%)	3.9	5
Extract (%)	87.6	89.3
Color (SRM)	1.68	1.35
Beta-glucan (mg/L)	365	102
Soluble protein (%)	4.1	3.92
Protein (%)	9.2	8.8
S/T (%)	44.6	44.5
FAN (%)	154	140
DP (°L)	84	77
Alpha amylase	48.7	45
Filtration time	Normal	Normal
Clarity	Hazy	Hazy
pH	5.99	5.78
Friability[a] (%)	70.6	96.4

FAN = Free amino nitrogen.
DP = Diastatic power.
S/T = Soluble/total protein.
[a] Friability measured at OSU.

of malt produced from naked barley.

As reviewed by Meints and Hayes (2019), only a few studies have been conducted on brewing with naked barley malt. These initial studies were conducted using malts with various ratios of naked to covered barley and the resulting beer was acceptable under sensory evaluations. In order to better understand how naked barley performs under different lautering methods, malt from Buck was evaluated using two systems, a mash filter and a lauter tun in collaboration with the OSU Fermentation Science Program. Both systems used 32.2 kg of malt and 10% rice hulls by dry weight were added as an adjunct. The ultimate goal of this preliminary experiment was to determine the functionality of naked barley malt using these two different brewing systems. Neither system showed any issues with filtration, and it was found that the beers were very similar in most aspects with the biggest difference in the degrees of fermentation and original gravity (Table 3). The degree of fermentation indicates the attenuation, or the degree of which sugar has been fermented by the yeast and converted into alcohol (Holle and Klimovitz, 2003). The lauter tun beer had a higher original gravity (fermentable and non-fermentable materials prior to fermentation) as well as a higher real degree of fermentation (RDF). These differences did not substantially impact the end quality of either beer. Based on a triangle test sensory analysis with 12 panelists replicated three times, no significant aromatic differences were observed between the two beers (p-value = 0.45, Z = 0.12). These observational data show that while brewing with naked barley is possible using current lautering technologies, variety improvement and analysis is necessary to reach high quality standards set by beers brewed using covered barley malts. Two follow-up studies will be conducted at Oregon State University with collaboration between the Barley Breeding Program and the Fermentation Science Program to look at differences in functionality and flavor both between varieties and brewing systems and using five blends of naked and covered malt.

As reviewed by Meints and Hayes (2019), distilleries have also become increasing interested in the use of naked barley for whiskey production. It has been found that malt modification may play a more crucial role than the hull for rapid filtration (Swanston and Middlefell-Williams, 2012). Naked barley with a modified malting regime was found to have acceptable levels of amyloytic enzymes and higher predicted spirit yield than the covered barley check (Agu et al., 2009). A recent study conducted by The Family Jones distillery (https://thefamilyjones.co/) in collaboration with the OSU barley breeding program compared the production of grain-on malt whiskey made with naked (Buck) vs. covered ('Lightning') barley malt. Sensory panelists were able to perceive a difference in flavor with a triangle test; the whiskey made from naked barley malt was determined to have reduced cereal, feinty, and pungent characters. It was established that an acceptable whiskey can be made from naked malt using this method. While more research needs to be conducted on malt protocols for both brewing and distilling end uses, naked barley seems to be a satisfactory alternative to covered barley.

Table 3
Beer quality analysis from two beers made with 100% naked barley malt. Brewing and analysis done with OSU Fermentation Science.

Parameters	Mash Filter	Lauter Tun
ABV (%)	5.1	5.
ABW (%)	4.0	4.3
RE (%)	4.1	4.0
AE (%)	2.2	2.0
OG (%)	11.9	12.3
RDF (%)	67.2	69.1
ADF (%)	81.5	83.8
Calories	156	161
Color (L)	2.8	3.1

ABV = Alcohol by volume.
ABW = Alcohol by weight.
RE = Realized extract.
AE = Actual extract.
OG = Original gravity.
RDF = Real degree of fermentation.
ADF = Actual degree of fermentation.

8. Feed and biofuel quality

Although most feed barley has been bred with an adhering hull, this is a consequence of the fact that many feed varieties are lines that didn't meet the malting profile. However, the hull is primarily made up of insoluble fiber, which provides no nutritional benefit for animals with monogastric digestive systems and can be supplemented in ruminant diets. As a result, in the 1970s, Canadian researchers began breeding naked feed barley for monogastric animals, specifically swine. They saw great success and at its height, naked barley production in western Canada reached 303,514 ha by 1997 with 24 varieties released (Rossnagel, 1999). Naked barley has several advantages as a feed over corn or covered barley; it contains higher levels of protein and has higher levels of digestible energy (up to 15% more) because the crude fiber content in the hull creates a dilution effect (Bhatty, 1999).

Naked barley has shown to be a superior feed to covered barley for pigs, but it can also be a successful feed for poultry and cattle as well (Thacker et al., 1988; Fellner et al., 2008). A recent study conducted by the OSU Poultry Extension team in collaboration with the OSU Barley Breeding program looked at effects of including naked barley with moderate beta-glucan levels as a part of a diet fed to layer and broiler chickens. Feeding barley to poultry can be problematic because poultry lack enzymes to properly digest beta-glucans and other forms of fiber. Because the beta-glucan is highly water soluble, this can increase the viscosity of intestinal fluids, leading to a condition known as 'sticky droppings' (Classen et al., 1985). However, with the lack of the hull, which contains insoluble fiber, it was hypothesized that the chickens would respond more positively to a diet containing naked barley. Preliminary analysis of a layer feeding trial conducted at OSU found that layer performance and egg quality was not affected by the inclusion of #STRKR naked barley up to 50% in the diet formulation. Other recent feeding studies have shown that a naked barley diet in lactating cattle did not result in milk fat depression or a decrease in milk yield, indicating that naked barley can be a sufficient energy source for high-producing lactating cows when the feeding diets contain 30% barley or less (Yang et al., 2018).

Fuel ethanol is another end-use for naked barley that has been explored by researchers in the US and elsewhere. There has been previous interest in using corn as a biofuel, but increased demand resulted in other grains, including barley, being considered for ethanol production (Griffey et al., 2010). Because naked barley has higher starch content and a higher nutritional feed value, with 8–14% more digestible energy than covered barley (Bhatty, 1979), which is important for efficient production of ethanol, it was investigated as a potential alternative to corn and wheat for fuel alcohol production. Griffey et al. (2010) concluded that the ideal naked barley for ethanol production would have high starch and protein and low beta-glucan and fiber concentration. Ingledew et al. (1995) concluded that naked barley could successfully be used for fuel alcohol production and observed no problems with the fermentation process. However, despite this research, fuel ethanol production did not end up becoming a major end-use for naked barley as a result of corn subsidies.

9. Conclusions

Although Buck and #STRKR were initially bred for food-end-uses (Meints et al., 2015b, 2018), they have been shown to have decent malt quality and produced satisfactory beers. Additionally, in initial feeding studies, they perform well as part of a poultry diet, resulting in no undesirable effects. These lines are examples of naked germplasm with moderate beta-glucan levels that can be classified as "multi-use" even though they were initially selected for only one end-use. However with more targeted breeding and patience, varieties can be developed that show excellent quality for all three end-uses. With the genetic resources from around the world that are available in USDA-GRIN and other germplasm repositories and using breeding tools such as marker-assisted selection (Meints et al., 2015), genomic selection (ongoing research), and potentially CRISPR-Cas9 (Gerasimova et al., 2020) and continued research on end-use quality, advances can be made to create a new frontier of naked barley for multiple end-uses that will benefit growers, processors, and consumers.

Author statement

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Declaration of competing interest

The authors declare no conflict of interest.

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