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Influence of Corn Size Distribution on the Diastatic Power of Malted Barley and Its Impact on Other Malt Quality Parameters

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Detailed studies were carried out on the influence of corn size distribution on the values obtained for diastatic power (DP) of commercially malted barley. Malted barley was screened using a screening box, and the DP activities of the different corns retained on the different compartments of the screening box were determined. The malt samples retained on the 2.8 mm screen had the highest DP activity, whereas the small corns (≤2.2 mm) had the lowest levels of DP activity. When the DP results of the corns retained on the different screens were weighed in relation to the percentages of grains retained on each screen, the results obtained were very similar to those obtained from the mixed, unscreened malt samples. The results indicate that the higher the percentage of large corns in a malt sample, the higher the levels of DP found in the malts. In malt samples from both the Decanter and Maresi varieties/cultivars, regression analysis showed that large corns accounted for 87% of the variation in DP. These studies confirmed that corn size distribution is a very important factor in determining the DP level of malted barley. The study is of commercial significance because within a variety, with a similar range of nitrogen, large corns produce malt of higher DP. When the percentage of large corns is high, this should give extract with improved fermentability (yield of fermentable sugars). The gelatinization properties of different grain size fractions, some of which were malted individually, were also studied using a rapid visco analyzer (RVA), and this showed that kernel size had an important impact on the physical properties and malting performance.

KEYWORDS: Corn size distribution; diastatic power; malt quality; rapid visco analysis

INTRODUCTION

Malted barley is a key ingredient in many industrial processes, especially in the brewing and distilling industries. It is also used extensively in the manufacture of non-alcoholic drinks and malt beverages and as an ingredient for baked products, as well as in the syrup extract industry. In the production of cereal-based spirits such as Scotch grain whisky, as well as in brewing, it is necessary to use malted barley to digest both the main adjunct substrates (typically wheat or corn) and that deriving from the malt itself. Because only a small quantity of barley malt is used in the production of grain whisky, it is essential that it contains a very high level of starch-degrading enzyme activity, which is defined in terms of diastatic power (DP). DP has long been recognized by maltsters, brewers, and distillers as a fundamental determinant of the quality of malted barley (*1*, *2*), and it has been reported that variations in this parameter can be affected by many factors (*2*−*4*).

Total nitrogen and β-glucan contents are also considered to be very important quality parameters in the assessment of malting barley, and these parameters have also received extensive attention in research studies (*3*, *5*−*19*). Another important parameter that is known to influence the quality of malting barley is the corn (kernel) size. This has resulted in the screening of barley samples prior to malting not only to remove foreign matter but also to separate a large proportion of the very thin corns present in the barley sample prior to malting. In the malting industry these are usually removed by passing the barley over a mesh screen. This is because, when there is a wide range of corn sizes, grain modification will not be uniform as grains of different sizes will modify at different rates during malting (*20*, *21*). Screening of barley is also an established means of assessing and selecting barley quality for malting and is usually defined in commercial contracts. Although the presence of thin corns is known to affect the quality of malting barley, the relationship between the corn size distributions and how they influence the actual DP results for commercial malt samples is not well understood.

In this study, we have reported the results of detailed investigations into the relative impact of large and small (thin) corns on the quality of malted barley and, in particular, how

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they affect the results of the diastatic power of malt. The study was primarily focused on commercially produced malt as finished product, and development of DP during malting was not studied in all cases.

In the second part of the study, barley was separated (before malting) into fractions by sieving, and the different fractions were micromalted. The aim of this part of the study was not to simulate commercial production of malt but to consider some of the changes that are likely to occur when different corn size distributions are present in a sample of barley. This is therefore very different from commercial malting practice, which comprises the focus of the main study.

MATERIALS AND METHODS

Commercially Malted Barley Samples. Commercially malted barley was obtained from two different malting companies, A and B. The samples were from four separate batches of malt (representing two U.K. spring barley varieties, Decanter and Maresi) from each of the maltings. Thus, a total of eight different malt samples from each malting were studied. A detailed malting protocol was not provided by the malting companies, but was assumed to be typical of commercial malting practice in United Kingdom/Scotland. The malt samples obtained from malting company A were made from Decanter (Kjeldahl total nitrogen = 1.9%), whereas the malt samples obtained from malting company B were produced from Maresi (Kjeldahl total nitrogen = 1.7%). Although the malt samples from the different malting companies had different nitrogen levels (Kjeldahl method), it is important to remember that the focus of the study was to show how the proportion of the different corn sizes affects the determination of the final DP value, rather than to investigate the effect of nitrogen on the DP of malted barley.

Corn Size Distribution of Barley Malt. A standard Institute of Brewing screening box method (*22*) was used to characterize the corn size distribution of samples of barley malt. In this method, 100 g of barley malt was transferred to the screening box (2.8 mm; 2.5 mm; 2.2 mm; and bottoms) and shaken vigorously for 2 min. The grains collected in each compartment of the screening box after shaking were weighed, and the composition was expressed as a percentage of the total. The screening box method described above has been used elsewhere and has been validated by comparison with a Marvin digital seed analyzer (*23*). In similar studies reported by other workers (*4*), screening of barley has been performed for 1 min using a Sortimat sieving apparatus.

Determination of Diastatic Power of Barley Malt. Barley malt DP was determined by using the Fehling's solution procedure following a procedure described in the Institute of Brewing's *Recommended Methods of Analysis* (*24*). DP based on Lintner starch (Fisher Chemical Starch, Lintner's) is reported as °Lintner (°L). Fehling's solutions A and B were supplied by BDH Chemicals. Samples were analyzed in triplicate, and duplicate results that did not exceed ±5% were used in the calculation of DP values.

Laboratory Malting of Barley. Barley was sieved using the screening box as described above, and the fractions were micromalted using a standard protocol as described below. Barley samples were steeped at 16 °C by immersion in water for 8 h, followed by 16 h of air rest, followed by 24 h of immersion. Samples were micromalted at Heriot-Watt University using Custom Laboratory Products micromalting equipment (Keith, Banffshire). Grain was germinated at 16 °C for 4 and 5 days. Samples were kilned at 50 °C (Seeger Kiln, Seeger Machinenfabrik, Fellback, Germany) for 16 h and derooted by hand to give the finished malt.

Viscometric Properties of Barley and Malt—Rapid Visco Analysis (RVA). Studies of the viscometric properties of commercially malted barley, together with unmalted barley and laboratory micromalted samples, were carried out using a Newport Scientific Rapid Visco Analyser (RVA) instrument supplied by Calibre Control (Asher Court Lyncastleway, Appleton, Warrington, U.K.) that was operated according to the manufacturer's instructions (*25*). The Rapid Visco Analyser is a rotational continuously recording viscometer, specifically configured for starch-based materials. This has heating, cooling, and variable shear capabilities, in which a slurry of sample flour with water can be subjected to a temperature program to analyze its pasting and gelatinization properties. This instrument profiles the starch and gelatinization properties of a given sample. The RVA program used for unmalted barley was different from that of malted barley.

Table 1. RVA Program for Unmalted Barley

time (min:s)	temperature (°C)	speed (rpm)
0:00	50	960
0:10	50	160
1:00	50	160
4:42	95	160
7:12	95	160
11:00	50	160
13:00	50	end

Table 2. RVA Program for Malted Barley

time (min:s)	temperature (°C)	speed (rpm)
0:00	30	960
0:10	30	75
27:00	69	75
30:00	69	end

Rapid Visco Analysis Program for Unmalted Barley. A calculated amount of sample (approximately 3.0 g for unmalted barley), adjusted for moisture (*25*), was slurried with a measured amount of water (25 g) to give a total weight of approximately 28 g and then processed in the RVA analyzer using a program set up for unmalted cereals, which takes 13 min to run (**Table 1**).

Rapid Visco Analysis Program for Malted Barley. A different RVA program is required for malted barley, and this is described below. A calculated amount of sample (approximately 9.3 g for malt), adjusted for moisture (*25*), was slurried with a measured amount of water (18.7 g) to give a total weight of 28 g and then processed in the RVA analyzer using a 30 min program set up for malted barley (**Table 2**). The action of endogenous malt enzymes on the starch results in a RVA profile which is quite distinct from that of unmalted barley.

RESULTS AND DISCUSSION

The results in **Table 3** show the corn size distributions of four different batches of malted barley (Decanter) produced industrially by malting company A. It is clear from the results shown in **Table 3** that the different batches of the malt samples made by this malting plant had different distributions of large and small corns. Sample 1 had the highest percentage of large corns (>2.8 mm), which accounted for 84% of the total grain size distribution of this sample. Sample 4 had the smallest percentage of large corns at 74.8%. This sample also produced the highest proportions of thin corns (<2.5 mm) and bottom corns (<2.2 mm). **Table 3** also compares the results for DP of the original malt samples with those of the individual fractions collected on each of the screens. The fraction of barley malt retained on the 2.8 mm screen (the fraction containing the highest proportion of large corns) gave an average DP value of 164.5, which was higher than either the value obtained for the unscreened sample or the DP values for any of the other fractions. DP was seen to decrease with decreasing corn size, with the malt grains collected in the bottom compartment (<2.2 mm) giving the lowest DP values. Results of an analysis of variance (**Table 4**), comparing the data for the four fractions, confirmed a highly significant difference ($p = 0.0001$) in DP according to corn size.

In all, the results suggest that malt DP will be substantially influenced by the relative amounts of the corns retained on the

Table 3. Percentage Corn Size Distribution and Contribution of Corn Size to the Overall DP (°L) of Malted Barley from Malt Samples Supplied by Malting Company A

	sample 1			sample 2			sample 3			sample 4		
	DP	fraction (%)	contribution to DP (%)	DP	fraction (%)	contribution to DP (%)	DP	fraction (%)	contribution to DP(%)	DP	fraction (%)	contribution to DP (%)
mixed grains	154	100	100	160	100	100	160	100	100	162	100	100
>2.8 mm	156	84	85.1	166	80.3	83.3	166	77.2	80.1	170	74.8	78.5
2.5–2.8 mm	152	11.5	11.4	156	12.7	12.4	156	14.6	14.2	156	14.1	13.6
2.2–2.5 mm	152	3.1	3.1	148	5.2	4.8	152	6.1	5.8	152	6.2	5.8
bottom (<2.2 mm)	128	1.4	1.2	130	1.8	1.5	136	2.1	1.8	102	4.5	2.8

Table 4. Analysis of Variance Comparing the DP Values between the Four Corn Sizes (Company A)

due to	sum of squares	DoF	mean square	*F* stat	signif
main effects	3618.750	3	1206.250	17.848	0.0001
corn size	3618.750	3	1206.250	17.848	0.0001
explained	3618.750	3	1206.250	17.848	0.0001
error	811.000	12	67.583		
total	4429.750	15	295.317		

different compartments of the sieve box, with the large corns (>2.8 mm) contributing higher DP levels (**Table 3**). When the DP results obtained from the different sieve fractions were averaged and compared with the DP of those obtained from the unscreened sample, it was evident that a simple averaging of the results of the DP analysis, obtained from the malt from the different sieve compartments, did not reflect the actual DP results obtained from the original unscreened malt. DP results obtained from this simple averaging were between 4.5 and 10.5% lower than the actual results of DP obtained from the original unscreened malt.

However, when the average DP results obtained from the malt samples retained on the compartments of the sieves were mathematically weighted to reflect their correct proportions in each fraction, DP results similar to those for the original malt sample were found. The results (**Table 3**) clearly show not only that the corn size affected the DP of the malt but also that the proportion (percentage) of the different sizes of grains present in the malt sample played a very important role with regard to the calculation of the DP. Although the results further show that the greater the percentage of large corns in the sample, the more DP would be obtainable from that malt. The results obtained for the malt samples made from another barley variety (Maresi, company B) gave different DP levels (**Tables 5** and **6**), but agreed with the conclusion that the highest DP values are obtained for fractions with the largest corn size, as observed for the malt samples made from Decanter from company A.

Other workers in different laboratories have investigated various factors that affect grain and malt quality (*4*, *26*−*28*). The results of one study (*29*) did show that "intermediate" kernels developed higher DP activity than "plump" kernels. The results of our micromalting studies also showed that the 2.2 mm sieved malt had higher DP activity (91 °L) when compared with the DP result obtained for >2.2 mm sieved malt (83 °L) or the DP result obtained for unscreened malt (83 °L). The higher DP results obtained from malts made in the laboratory from thin corns or intermediate kernels in these studies, in contrast to the lower DP results obtained from commercially made malts from corns of similar size, may be due to differences in the kilning methods.

During the commercial production of some malt, germinated grains are kilned at progressively increased temperatures, including the "curing" temperature at over 85 °C, for color and flavor development in the malt. High curing temperatures will definitely denature some of the heat labile enzymes such as β-amylase, which is usually measured as DP. Moreover, heat transfer during the kilning process in commercial malting, where large batches (over 20 tonnes, i.e., 20000 kg) of germinated grains are kilned, followed by subsequent heat retention in the bulk of malt after the kilning process will further reduce activity of heat labile enzymes. This is very different from laboratory malting conditions, where small-scale malting is carried out. The kilning process in commercial malting will lead to reduced levels of DP of the malt. It is not clear at present how any reduction in DP activity in commercial malt, especially during the curing phase of the kilning process, will affect enzyme reduction in corns of different sizes. This requires more detailed investigation.

RVA analyses of corn size distributions in commercially malted barley were investigated. Barley malt was sieved and separated into corn size fractions as described under Materials and Methods, and the malt samples collected in the different sieve compartments (>2.5 mm; 2.2−2.5 mm; <2.2 mm) were assessed using a RVA. The RVA provides a rapid analysis of the viscosity and gelatinization properties of cereal samples, allowing qualitative comparison or the profiles of different samples and providing some indicators to the behavior and properties of major cereal components, primarily starch (*25*).

Figure 1 shows the RVA viscosity profile obtained when commercial malt fractions collected from the different sieve compartments were run through the RVA equipment. It is evident from **Figure 1** that the RVA viscosity results for malt samples from the different sieve fractions of the commercial malt are very low. In contrast, when a barley sample was sieved into fractions (>2.2 mm; ≤2.2 mm; unscreened) prior to malting and then malted separately in the laboratory (under the same laboratory malting conditions), and the malts obtained from the sieved barley samples were analyzed using the RVA equipment, the viscosity results (**Figure 2**) were substantially higher than those obtained from commercial malt. The micromalting results show that uniform modification of barley will be difficult to achieve in different parts of a commercial germination vessel due to wide variations in corn size distribution (*20*, *21*).

The results further show that although RVA peak viscosities of the micromalted barley samples are much higher, there is the potential for some "improvement" of commercial malting process by tighter control on corn sizes used for malting to increase the level of DP. This is an advantage to the whisky industry as more is better, as this will result in higher spirit yield per tonne of malt/barley. However, in other brewing sectors this may not necessarily be the situation, as the brewer will be interested in not only alcohol content but also the final gravity of the beer, which will influence beer mouthfeel (palate fullness). Another important observation from the results in **Figure 2** is the differences occurring within the ungelatinized starch granules

Table 5. Percentage Corn Size Distribution and Contribution of Corn Size to the Overall DP (°L) of Malted Barley from Malt Samples Supplied by Malting Company B

	sample 1			sample 2			sample 3			sample 4		
	DP	fraction (%)	contribution to DP (%)	DP	fraction (%)	contribution to DP (%)	DP	fraction (%)	contribution to DP (%)	DP	fraction (%)	contribution to DP (%)
mixed grains	194	100	100	210	100	100	190	100	100	186	100	100
>2.8 mm	204	79.8	83.9	222	74.3	78.5	200	79.7	83.9	194	79.7	83.1
2.5–2.8 mm	186	12.2	11.7	204	12	11.7	180	9.5	9	166	11.4	10.2
2.2–2.5 mm	172	5	4.4	176	7.4	6.2	162	6.1	5.2	160	5.1	4.4
bottom (<2.2 mm)	114	3.1	1.8	136	6.2	4	100	4.9	2.6	114	3.8	2.3

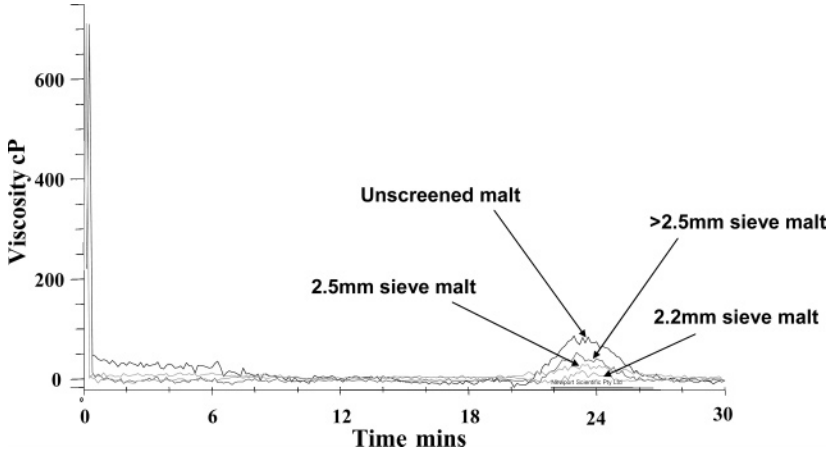

Figure 1. RVA profile of separated fractions (>2.5 mm; 2.5 mm; ≤2.2 mm) of commercially produced barley malt (size fractions separated after malting).

Table 6. Analysis of Variance Comparing the DP Values between the Four Corn Sizes (Company B)

due to	sum of squares	DoF	mean square	*F* stat	signif
main effects	17316.750	3	5772.250	34.240	0.0001
corn size	17316.750	3	5772.250	34.240	0.0001
explained	17316.750	3	5772.250	34.240	0.0001
error	2023.000	12	168.583		
total	19339.750	15	1289.317		

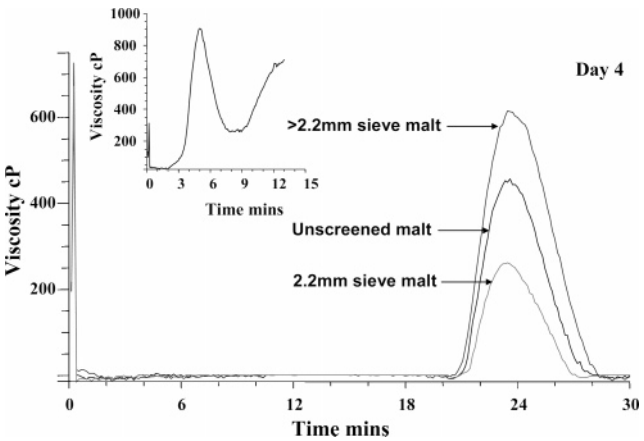

Figure 2. RVA profiles of individual fractions of barley malt (>2.2 mm; ≤2.2 mm; unscreened) micromalted separately for 4 days. (Inset) RVA profile of the original unscreened barley, which is shown as an illustration.

of the different corn sizes when they are malted separately. Pitting of the starch granules will result in the cleavage of the amylose and amylopectin polymers of the starch granules. The reduced size of the amylose and amylopectin polymers will then allow the starch polymers to "slide" past each other more easily, resulting in lower viscosity. This would be expected to produce the type of RVA viscosity profile observed in **Figure 1**.

Again, micromalting of the sieved barley samples (used for illustration) enabled control of excessive corn germination by optimally stopping germination for individual samples, by removing them from the germination vessel (based on visual observation of acrospire and rootlet growth). This is possible because the sieved samples can be monitored and were observed to produce rootlets and shoots at different rates. Therefore, germination can be stopped when any part of the germinating grains starts to produce excessive rootlets and shoots. This explains the type of RVA viscosity results presented in **Figure 2**. The major shortfall in this controlled type of laboratory malting process is that adequate modification of endosperm materials of barley may not be achieved when the germination process is terminated; hence, the pasting viscosity of the starch present in the malt samples will be relatively high, but still lower in magnitude when compared with the pasting viscosity of the starch present in the original barley from which the malts were made. This can be seen in the RVA profile of unmalted barley, which is shown for illustration in the inset in **Figure 2**. This part of the study highlights the latent changes that are likely to occur when mixed fractions of barley sample are subjected to the malting process. It should be emphasized that the laboratory malting process described here is very different from what would be obtained in practice in a commercial malting, where malting grains are not separated into different fractions prior to malting. However, the experiments do give an insight into the different potential malting properties of individual corn size fractions.

It is evident from the charts (**Figure 2**) that the RVA profile of the unmalted barley and the RVA profiles of the micromalts from the sieved barley fractions samples were quite different because different programs were used to run the samples (see Materials and Methods). Unmalted barley has a higher peak viscosity (above >800 cP) than the malt fractions and also has a breakdown zone and final viscosity (>700 cP), which were absent in the malt samples. In both RVA programs (for malted

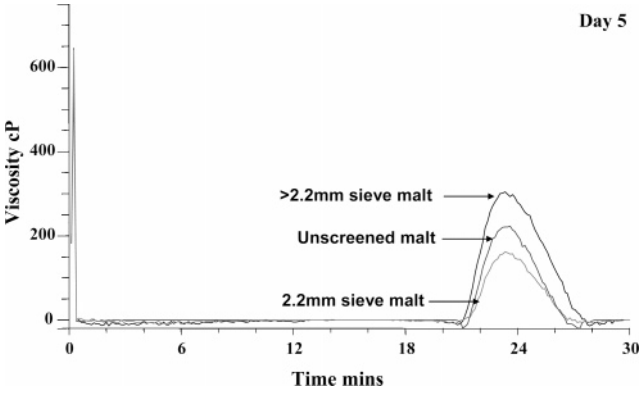

Figure 3. RVA profiles of individual fractions of barley malt (>2.2 mm; ≤2.2 mm; unscreened) micromalted separately for 5 days.

and unmalted barley), as the RVA program temperature rises, the native starch of barley will gelatinize to form a highly viscous gel, which is registered as RVA viscosity. This is consistent with established knowledge relating to unmalted cereals (*25*, *30*). Although the RVA profiles of barley and malt are different (**Figure 2**), it is important to note that the RVA pasting times for both the commercially and laboratory produced malts were similar at 24 min (**Figures 1** and **2**) because they were both run on programs designed for barley malt. However, the differences in peak viscosities, which indicate the viscous load of the sample and relate to the starch present in the sample (*25*), clearly show that the commercial malt sample has low peak viscosity in contrast to the higher peak viscosity of micromalted barley, because the micromalted barley was poorly modified as germination was terminated before adequate modification was achieved during the malting process. In commercial malting practice, extended periods of germination can help to achieve adequate modification, and experienced maltsters can estimate when adequate modification has been achieved. One way experienced maltsters quickly gauge the extent of modification is to squeeze and roll out the "dough" (modifying endosperm) between their fingers to judge its consistency (personal observation).

Most importantly, the RVA profile of the malted fractions showed peak viscosity, which decreased according to the corn size distribution of the malted barley, with large corns having higher peak viscosity (>600 cP) and thin (small) corns having the least peak viscosity (ca. 200 cP). Palmer (*31*) notes that large corns are normally associated with higher levels of starch than thin corns. This goes some way to explaining why the RVA peak viscosity of the large corns was higher than that of the thin corns. This further confirms that corns of different sizes will modify at different rates. The RVA viscosity results shown in **Figure 2** were obtained when barley was malted for 4 days. When the barley was malted for 5 days, the RVA viscosity results presented in **Figure 3** were obtained. It is evident that the RVA viscosity results shown in **Figure 3** are lower than those shown in **Figure 2** and are more similar to commercial malt. This shows that as germination progresses, further hydrolysis of the starch chains will further reduce peak viscosity. The large difference in the RVA profiles observed for day 4 and 5 malted barley also shows that if germination was further extended to 6 or 7 days, for example, to compensate for uneven germination in a mixed barley sample, more reducing sugars will be produced with higher malting loss. This will produce malt that is more highly or overly modified and would be expected to give a RVA profile similar to that shown in **Figure 1** for commercial malt.

This study has shown that the proportions of the different corn sizes can be controlled to produce malt of higher diastatic power when greater proportions of larger corns are malted. Corn size distribution will also affect the overall modification pattern of barley during malting, which, in turn, will have some effect on the final quality of malt. There is considerable commercial significance in these results because not only will large corns produce malt of higher DP, they will by extension yield extract that is more fermentable so as to increase alcohol yield (*20*). This is of benefit in some brewing production systems such as with whisky. Therefore, in appropriate commercial transactions (i.e., whisky), it is important to purchase malt with a higher percentage of large corns and a lower percentage of thin corns to obtain good value for money because malt is relatively expensive compared to unmalted adjunct. This paper illustrates how it is possible to use relatively simple physicochemical techniques to improve the understanding of the more complex biochemistry underlying the transition from barley to malt and how this can potentially influence the properties of the final malt.

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LITERATURE CITED

(1) Palmer, G. H. Cereals in malting and brewing—starch structure and degradation. In *Cereal Science and Technology*; Palmer, G. H., Ed.; Aberdeen University Press: Aberdeen, Scotland, 1989; p 155.

(2) Agu, R. C. Quality assessment and performance of malted barley for food processing. *MBAA Tech. Q.* **2005**, *42* (3), 199−203.

(3) Agu, R. C. Some relationships between malted barleys of different nitrogen levels and the wort properties. *J. Inst. Brew.* **2003**, *109*, 106−109.

(4) Arends, A. M.; Fox, G. P.; Henry, R. J.; Marschke, R. J.; Symons, M. H. Genetic and environmental variation in the diastatic power of Australian barley. *J. Cereal Sci.* **1995**, *21*, 63−70.

(5) Agu, R. C.; Palmer, G. H. Enzymic modification of endosperm proteins of sorghum at different malting temperatures. *J. Inst. Brew.* **1996**, *103*, 415−418.

(6) Agu, R. C.; Palmer, G. H. Some relationships between the protein nitrogen of barley and the production of amylolytic enzymes during malting. *J. Inst. Brew.* **1998**, *104*, 273−276.

(7) Agu, R. C.; Palmer, G. H. The effect of nitrogen level on the performance of malting barley varieties during germination. *J. Inst. Brew.* **2001**, *107*, 93−98.

(8) Jones, B. L. Interactions of malt and barley (*Hordeum vulgare* L.) endoproteinases with their endogenous inhibitors. *J. Agric. Food Chem.* **2001**, *49*, 5975−5981.

(9) Jones, B. L.; Marinac, L. A. Purification, identification and partial characterization of a barley protein that inhibits green malt endoproteinases. *J. Am. Soc. Brew. Chem.* **1997**, *53*, 160−166.

(10) Jones, B. L.; Marinac, L. A. Purification and partial characterization of a second cysteine proteinase inhibitor from ungerminated barley (*Hordeum vulgare* L.). *J. Agric. Food Chem.* **2000**, *48*, 257−264.

(11) Zhang, N.; Jones, B. L. Development of proteolytic activities during barley malting and their localisation in the green malt kernel. *J. Cereal Sci.* **1995**, *22*, 147−155.

(12) Bourne, D. T.; Jones, M.; Pierce, J. S. Beta glucan and β-glucanases in malting and brewing. *Tech. Q. Master Brew. Assoc. Am.* **1976**, *13*, 3−7.

(13) Chen, L.; Sadek, M.; Stone, B. A.; Brownlee, R. T. C.; Fincher, G. B.; Hoj, P. B. Stereochemical course of glucan hydrolysis by barley (1,3)(1,4)-β-glucans. *Biochim. Biophys. Acta* **1995**, *1253*, 112−116.

(14) Henry, R. J. Changes in β-glucan and other carbohydrate components of barley during malting. *J. Sci. Food Agric*. **1988**, *42*, 333−341.

(15) Home, S.; Pietila, K.; Sjoholm, K. Control of glucanolysis in mashing. *J. Am. Soc. Brew. Chem.* **1993**, *51*, 108−113.

(16) Jin, Y. L.; Speers, R. A.; Paulson, A. T.; Stewart, R. J. Barley β-glucan and their degradation during malting and brewing. *Tech. Q. Master Brew. Assoc. Am.* **2004**, *41*, 231−240.

(17) Palmer, G. H. Malt performance is more related to inhomogeneity of protein and β-glucan breakdown than to standard malt analyses. *J. Inst. Brew*. **2000**, *106*, 189−192.

(18) Palmer, G. H.; Agu, R. C. Effect of mashing temperatures and endo-β-glucanases on β-glucan content of malt worts. *J. Inst. Brew*. **1999**, *105*, 233−235.

(19) Palmer, G. H.; Mackenzie, C. I. Levels of alkali-soluble β-D-glucans in cereal grains. *J. Inst. Brew*. **1986**, *92*, 461−474.

(20) Palmer, G. H. Achieving homogeneity in malting. *Proceedings of the European Brewery Convention Congress*, Cannes; IRL Press: Oxford, U.K., 1999; pp 323−363.

(21) Palmer, G. H. Cereals in malting and brewing—steeping and germination. In *Cereal Science and Technology*; Palmer, G. H., Ed.; Aberdeen University Press: Aberdeen, Scotland, 1989; pp 130−131.

(22) The Analysis Committee of the Institute of Brewing (IOB)(1997). Method 1.13, sieving test for barley. *Recommended Methods of Analysis of the Institute of Brewing*; London, U.K., 1997.

(23) Swanston, J. S.; Smith, P. L.; Gillespie, T. L.; Brosnan, J. M.; Bringhurst, T. A.; Agu, R. C. Associations between grain characteristics and alcohol yield among soft wheat varieties. *J. Sci. Food Agric.* **2007**, *87*, 676−683.

(24) The Analysis Committee of the Institute of Brewing (IOB)(1986). Method 2.7.1. *Recommended Methods of Analysis of the Institute of Brewing*; London, U.K., 1986; pp 20−21.

(25) Newport Scientific. *Application Manual for the Rapid Visco Analyser*; Newport Scientific Pty. Ltd.: Warriewood, Australia, 1998; pp 19−26.

(26) Gibson, T. S.; Solah, V.; Glennie Holmes, M. R.; Taylor, H. R. Diastatic power in malted barley: contributions of malt parameters to its development and the potential of barley grain beta-amylase to predict malt diastatic power. *J. Inst. Brew*. **1995**, *101*, 277−280.

(27) Molina-Cano, J. L.; Ramo, T.; Ellis, R. P.; Swanston, J. S.; Bain, H.; Uribe-Echeverria, T.; Perez-Vendrell, A. M. Effect of grain composition on water uptake by malting barley: A genetic and environmental study. *J. Inst. Brew*. **1995**, *101*, 79−83.

(28) Swanston, J. S.; Ellis, R. P.; Rubio, A.; Perez-Vendrell, A.; Molina-Cano, J. L. Differences in malting performance between barleys grown in Spain and Scotland. *J. Inst. Brew*. **1995**, *101*, 261−265.

(29) Edney, M. J.; Izydorczyk, M. S.; Symons, S. J.; Woodbeck, N. Measuring barley kernel colour and size to predict end use of malt quality; available at www.grainscanada.gc.ca/pubs/research/edney_m/predict_quality/predict_qualitye.pdf.

(30) Agu, R. C.; Bringhurst, T. A.; Brosnan, J. M. Production of grain whisky and ethanol from wheat, maize and other cereals. *J. Inst. Brew*. **2006**, *112*, 314−323.

(31) Palmer, G. H. Cereals in malting and brewing—starch granule production in developing grain. In *Cereal Science and Technology*; Palmer, G. H., Ed.; Aberdeen University Press: Aberdeen, Scotland, 1989; p 68.

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