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Malting - 'the middle parts of fortune' - a history of innovation and the enduring quest for efficiency

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Abstract

Why was the work done: The malting process has long been a target for innovation to improve malt quality. The efficiency of utilisation of labour, capital, water and energy, particularly the energy intensive kilning process is a key target for maltsters to reduce the environmental footprint and costs. Similarly, water use during steeping is a priority due to scarcity of water and regulations regarding the disposal of wastewater.
How was the work done: A comprehensive review of the literature was undertaken to identify prospects for improving the efficiency of the malting process.
What are the main findings: The malting process involves: (i) selection of barley variety of suitable quality (protein, microbiologically sound); (ii) cleaning and grading; (iii) steeping in water with dry rests over one to two days, moisture increases from 10-13 to >40% (ideally 42-45%); (iv) germination at 12-16°C in a flow of humid air to maintain malt moisture at 42-46%; (v) kilning at between 50-85°C with hot dry air and (vi) storage and blending of malt to specification. Analysis of these steps shows that there is potential to reduce water use and discharge by ~40% with the Optisteep® system. In terms of energy, kilning uses 80-90% of all malting energy (conventionally gas), which makes kilning attractive for energy savings. Marginal energy savings can be made by lowing malt moisture to <40% before germination/kiln transfer and reducing malt moisture to <9% rather than 4-6%. Novel solutions include using green malt and barley brewing which save energy (especially kilning). Although for brewing with unkilned green malt, significant challenges remain to be solved. However, over the past 25 years, maltsters have been successful in incrementally reducing kilning energy by 20-35% per decade.
Why is the work important: Increasing malting efficiency while maintaining or improving quality has important implications for reducing costs and reducing the environmental footprint of the malting process.

Keywords

malting efficiency, malt quality, energy, water, steeping, germination, kilning

Introduction

The process of malting is old, very old. Dineley (2016), argues that the archaeological evidence for 'floor malting' extends back to the neo-lithic malting floors of Beidha, Jordan Valley (7000 BC), and Tell Ramad, Syria, 7000 BC. Dineley (2016), also hypothesised that the settlement of Ain Mallaha, Natufian Village (10,000-8,200 BC) contains structures that are consistent with early malting activities. Regardless, there can be little doubt that the Sumerian 'Hymn to Ninkasi' (c1800 BC), refers poetically to the malting process. A selected translated extract of is as follows:

'Ninkasi, you are the one who waters the malt set on the ground,
The noble dogs keep away even the potentates,
Ninkasi, you are the one who soaks the malt in a jar,
The waves rise, the waves fall.'

Over the millennia these prototype maltings have evolved into 'floor maltings' and their derivations (1300-1875) as eloquently described by Stopes (1885). Figure 1 shows the germination floor of a modern malting operation and equipment associated with floor maltings, which are largely manually operated. Latterly, excellent and comprehensive treatises on floor malting and their operations have been reported (Briggs 1998; Narziß et al. 2024).

During the second half of 19th century, malting equipment underwent a quantum leap in advancement. The evolution of pneumatic malting is generally associated with the Belgian-French malting equipment engineers, Nicholas Galland and Charles Saladin (Stopes 1885; Briggs 1998; Narziß et al. 2024). The pneumatic systems pioneered by Galland and Saladin between 1870-90, were a game changing improvement in the efficiency of the malting process. Driving (or drawing air) through the malt bed improved malt homogeneity and enabled larger barley pieces to be malted. This, combined with the mechanisation of the malt turning process, enabled larger maltings, improved malting consistency and reduction in manual labour. The use of air being drawn through the grain bed also enabled the optimisation of gases in the grain bed, particularly reducing the build-up of carbon

Figure 1.

Craft floor maltings. A. The germination floor being raked by visiting Fosters brewers Dermot O'Donnell and Peter Manders at Powell's Malt, (Victoria, Australia); B. A boby barrow for moving germinated grain at Tucker's Maltings (Devon, UK); C. Detail of a malt plough/rake at Crisp Malt (Norfolk, UK); D. A power shovel for shifting malt at Tucker's Maltings (Devon, UK). Images from Putman (2006, 2010).

dioxide (and other gases) that result from respiration of the germinated grain and associated microorganisms.

Comparing the floor malting in Figure 1 with the modern expressions of steeping, germination and kilning equipment (Figure 2) confirms the above observations. Whereas floor malting batch sizes are less than ~40t, modern maltings take advantage of economies of scale by efficiently handling batch sizes up to around 400t. The evolution of maltings between 1300-1875 is outlined by Stopes (1885), while the evolution of maltings during the modern era is summarised in Table 1. Interestingly, Griggs (2018) observed that malt produced by floor malting (commissioned ca. 1870), Saladin malting (commissioned in the 1950s) and modern circular maltings (commissioned in 1991) had similar analytical qualities for two different 2-row Winter barley varieties when malted by the Crisp Malting Group.

However, floor malted Maris Otter® showed clear differences in volatile composition when compared to a modern pneumatic malting. A similar comparison by Morrissy et al (2024) with pilot scale equipment reported broadly similar results for malt quality. However, a significant interaction was found between malting type and variety with respect to sensory results that was linked to proteolysis rate. This may be linked to a higher Kolbach index (KI) (potential Maillard reaction during kilning) which is correlated with greater flavour and desirability (Herb et al. 2017; Stewart et al. 2023).

The six stages of the malting process

Stage 1 - Barley grading and preparation for malting

Barley is unloaded at the malting plant either by truck, train or elevator. The grain is then cleaned and graded to remove foreign matter (stones, metal tools, etc.) and to remove thin grain which will not modify at the same rate as plump grain, nor mill efficiently (mill roller gap settings) and reduce malt extract (greater proportion of husk to endosperm). Maltsters expect to lose 5-10% of barley weight during cleaning and grading (Table 2). The cleaned

Figure 2.

Lay out of a modern pneumatic maltings (Joe White Malting, Perth, Australia). A. Steep fill and water addition; insert water spray during air rest period; B. Germination vessel with false stainless steel floor for air flow, note bed depth 'deep'; C. Kiln with false stainless-steel floor for air flow, note 'shallow' bed depth (c2008). Reproduced with permission of Boortmalt, Australia.

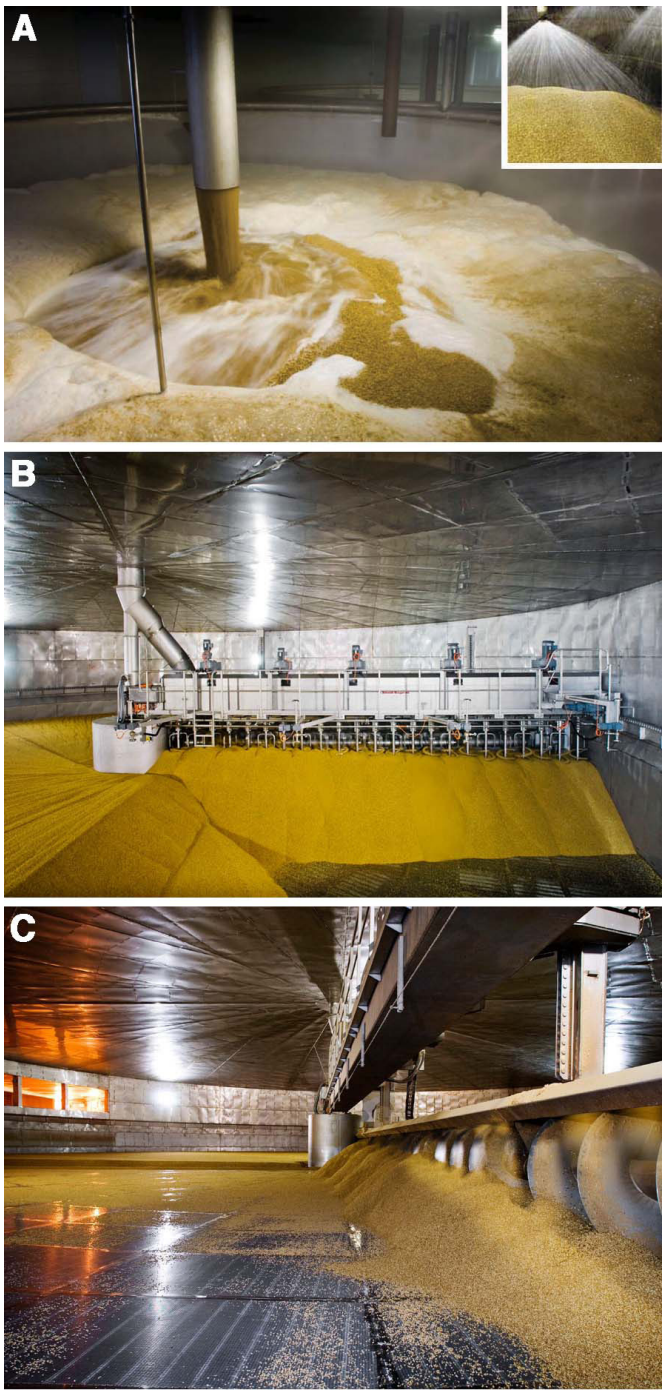

Table 1.

Modern pneumatic malting - steeping, germination and kilning vessels.

Steeping		
Flat bottomed 'ditch' steep	Antiquity	+ inexpensive to construct and simple - no aeration during immersion, low capacity, manual transfer, little temperature control
Cisterns (Stopes pattern or like)	<1885	+ self-filling/emptying, large tanks, low, hydrostatic pressure, better temp. control, aeration (later) - high capital cost, cleaning more difficult
Cylindroconical (non-aerated or not circular form < c1900)	c1950's	+ aeration, self-filling/emptying, low water use, easy cleaning, low capital cost - multiple small to medium tanks, medium to high hydrostatic pressure, less temperature control
Germination		
Saladin box (and Galland)	1840-80's	+ pneumatic aeration with turning screw, rectangular shape, batch size to 250 t - 'Archimedes' style screw causes minor damage
Wanderhaufen system (Galland)	~1880's	+ 'moving piece' forward over 4-5 days, pneumatic aeration, automation, rectangular - barley of similar malting characteristics, capital cost, small inter-batch mixing, size limited to 250 t
Drum malting (Galland)	~1890's	+ drum turning aeration with less grain damage, - limited to 90 t capacity, engineering/capital intensive
Flexi-box Germination/Kiln (G/K)	1960-70s	+ rectangular pneumatic aeration, capital cost reduced, one less transfer - less grain damage - bed depth not optimal for germination or kilning, size limited to 250 t
Tower malting	~1970's	+ circular, pneumatic aeration with rotating turner, gravity transfer, > 300 t grain load, site space efficient - capital intensive
Lausmann malting system	1979	+ automation, 'moving piece' forward over 4-5 days, pneumatic aeration, automation, not batch mixing - engineering and capital intensive, size limited to 250 t
Kilning		
Single deck kiln (Winkler/Mueger)	<1730's	- modern - higher airflow (7-10x germination) through grain bed, enable even pressure distribution, modern indirect heating perforated tiles, wired frames
Twin kiln (in UK, Tamplin & Sons)	<1881	- side by side single deck kilns to make double deck kiln - above and below decks ('tower kiln') - Blackman (pull) fan added <1885
Multideck kiln	<1850	- Two/three floors, top fresh germinated malt, bottom dry, air recirculation for energy efficiency
Continuous kiln	1960	- part tunnel of continuous-malting plant, that can have an annual production capacity of 7500 t. - management requires a continuous feed of green malt

From Stopes (1885); Hudson (1985); Briggs (1998); Kunze (1999); Patrick (2004); Oliver (2011); Mallett (2014); Yin (2021); Narziß et al (2024).

and graded grain is allocated to silos according to to variety, origin and protein content. In the future, greater focus is required on the content of grain protein and geographical source due to the relationship between protein and KI (Evans et al. 2023). Overall, these operations proceed at about 90+ tonnes/h in parallel with other malting operations (Table 3).

Table 2.

Malting losses.

Source of loss	Percentage loss
Barley cleaning & grading	5-10%
Steeping/leaching loss	1-1.5%
Respiration	3-5%
Rootlets	3-4%
Moisture	6-9.5%
Total malting loss (% weight)	**18-30%**

A malting loss of 20% per tonne as delivered is generally considered acceptable.

From Sallans and Anderson (1940); Ponton and Briggs (1969); Brookes (1984); Briggs (1998, 2004); Yin (2021); Narziß et al (2024).

Table 3.

Process timing in a modern pneumatic malting for pilsner/pale malt.

Malting Stage	Time span	Typical temperatures
Barley receival/storage	~90+t/h[1]	Ambient
Barley cleaning	~40+t/h[1]	Ambient
Steep	1-2d	12-16°C
Germination	3-5d	13-16°C
Kilning	24h[2]	1. Withering ~10h @ 50-60°C 2. Intermediate drying ~3-4h @ 65-75°C 3. Forced drying ~3-4h @ 75-80°C 4. Curing ~3-4h @ 80-85°C
Storage	>2 weeks	Ambient
Blending & dispatch	1-2h	Ambient
Total:	**5-8 days**	

Stage 2 - Steeping

The cleaned barley is transferred into one or more steeps (Figure 2A) depending on the capacity of the upcoming germination box. The objective of steeping is to hydrate the grain from a moisture content of 10-13% for the resting barley to >40% (ideally 42-45%) to promote germination (hydrolysis of proteins and non-starch polysaccharides) and the accumulation of hydrolytic enzymes (Yin 2021). Typically, modern steeps vessels are cylindroconical or in some malt houses, flat bottom. Briggs (1998) reported that water usage for conical steeps is 0.8 cubic m/t which is more efficient with flat bottom steeps at 1.3 cubic m/t. Table 4 and Yin (2021), indicates that water usage may be greater in different regions or malthouses. Maltsters generally allow one - two days for steeping (Table 3) dependent on the barley variety (dormancy), grain age (young and old typically slower) and if the use of gibberellic acid (GA) is permitted by the customer (Yin 2021). GA is typically added to steep waters at 1-2 mg/kg barley after chitting (Thomas 2014).

Generally, the steep program will entail 2-5 periods of immersion (wet) and dry rests with the temperature ideally 12-16°C. With a 24-hour steep regime, this will result in a steeping program of 8 hours wet, 8 hours dry and 7 hours wet. Alternatively, a two-day steeping program might be 8 hours wet, 8 hours dry, 8 hours wet, 8 hours dry, 7 hours wet, 7 hours dry and 2 hours wet. During the wet phases of steeping, air will be blown through the steep (c1950, Table 1) to rouse the barley, to avoid plugging and replenish oxygen for respiration. During the dry phases, water may also be sprayed on the barley to maintain optimal levels of water up take by the grain (Figure 2A) but the maltster needs to ensure even growth. Some steep configurations use two steep vessels with a transfer midway through steeping (Yousif and Evans 2020). Cylindroconical steeps generally have a capacity of less than 60 t to minimise the hydrological pressure on the barley/malt in the steep cone during immersion. Consequently, multiple steeps can be cast into germination boxes. Maltsters expect malting losses of 1-1.5% due to steep water leeching and washing (Table 2).

Stage 3 – Germination

The term 'germination' is widely used in the malting process but is a misnomer. As Bewley (1997) persuasively argued, physiologically a cereal grain is either germinated or dormant, with the transitory physiological processes between the two states relatively brief. 'Germination' begins when the wet (or dry) steeped barley is cast onto the perforated floor (allowing air flow) of circular or rectangular germination boxes or drums (Table 1). Turners in the box ensure a uniform bed depth post transfer. Many maltsters prefer the steep transfer to occur before chitting to avoid germ damage. It is shortly after chitting that exogenous GA (0.1-0.2 mg/kg) can be added, if permitted, via application by sprays (Thomas 2014). It should be noted that much less GA is required at this stage than if applied during steeping (1-2 mg/kg barley). Indeed, dry casting with actively chitted grain gives a much more rapid start to germination than wet casting when the surface moisture must be taken up before germination begins. GA enhances grain modification and hydrolytic enzyme accumulation (Yin 2021).

Typically, the germination phase in modern pneumatic malthouses (Table 1) requires three to five days at a controlled temperature, ideally 13-16°C (Table 3). Again, this is dependent on malthouse configuration, barley variety, grain age and if GA application is permitted. Typical grain bed depths in rectangular cylindrical boxes are about 1.0 m with helical-screw turners that turn the bed every 12 hours to avoid matting of rootlets and to promote air flow (Figure 2B). Water is periodically sprayed on the bed to ensure that the grain moisture peaks at 45% on day 2, with this is reduced to 38-40% on day 4 (MacLeod and Evans 2016). Air with high humidity (>95%) is blown through the malt bed to maintain a homogenous bed and avoid the build-up of CO_2 and 'hot spots' that impact grain homogeneity and physiology. Once the germination phase is complete, the grain is referred to as 'green malt.' The primary malting loss during germination is respiration (<5.0%) which is largely unavoidable as it is required to support the formation of hydrolytic enzymes and metabolic activities in the grain (Table 2).

Stage 4 – Kilning

The green malt is transferred to the kiln, a round box with a perforated floor to support efficient air flow (MacLeod and Evans 2016; Yin 2021). The kiln has turning rakes, similar to those in the germination box where the dynamics of drying the bed were first comprehensively explained by St. Johnston (1954). Ideally the kiln will have a depth ~1 m to facilitate even drying by not allowing the turning rakes to return wet grain to the bottom dry zone in the kiln so as to reduce kilning time (Figure 2C) (Briggs 1998). The objective of kilning is to stop the germination process by drying the grain with a program of dry, warm to increasingly hot air (Table 3). During the withering phase of kilning (12 hours at 50-60°C), metabolic activity in the grain will continue for a limited time due to inertia and the 'cooling' evaporation effect (Yousif and Evans 2020). The later phases of the drying process apply increasingly higher drying temperatures up to 80-85°C, used in the production of pale malt which accounts for >90% of malt production (Evans 2021). In the UK, higher air-on temperatures of 95-100°C can be used to produce ale malt (moisture 3%) with darker colours of 5-7°C EBC.

Some kiln configurations have more than one floor, with a transfer at the midway point, which is more gentle on some enzymes (Yousif and Evans 2020). Due to the lower effective moisture levels and higher sugar level in the malt, relatively temperature sensitive enzymes such as *beta*-amylase are more resistant to denaturation than might be expected (Frigon and Lee 1972; Back et al. 1979; Arakawa and Timasheff 1982; Evans et al. 1997; Yousif and Evans 2020). Maillard reactions (Hodge 1953; Ames 1988) are also promoted at malt curing temperatures which are combined with elevated concentrations ('low moisture') of simple sugars and free amino nitrogen (FAN). The Maillard products are an integral component of malt flavour and aroma.

Stage 5 - Storage

At the completion of kilning the grain is cooled and then cleaned by removal of rootlets, loose acrospires and small/ungerminated grain. The maltster should be careful as subsequent handling procedures can result in losses with dust, husk integrity and broken grain. Rootlet and loose acrospire removal are the primary malting losses (3-4%), which combine to produce an overall malting process loss between 18-30% (Table 2). Most maltsters are satisfied if these losses to kept to 20%. The malt is then stored for 2-4 weeks in silos together with other malt batches of comparable quality and variety. Bamforth et al (2009) identified the reason for this storage time with the level of thiol oxidase that negatively impact brewhouse performance (lautering performance) and which decreases with malt storage.

Stage 6 - Blending and dispatch

Once malt has been stored sufficiently long, the maltster will blend it with other malt batches to meet customer specifications. The malting process is inherently 'variable,' due to variety, production year and the geographical source of the barley (Evans et al. 2023). The maltsters primary strategy is to manage variation by blending. A practical outline of the influence of malt blending on malt quality can be appreciated by mashing trials with respect to extract, fermentability and lautering performance (Evans et al. (2012). The final requirement for the maltster is to transport (relatively fragile) malt to the customer. A basic requirement is any moisture pick up by the hydroscopic malt is kept to a bare minimum. Depending on location, trucks/lorries, containers or railway trucks are used.

Efficiency

The efficient use of inputs into any production process - be it malting or brewing - is critical for the sustainability and profitability of the business. Integral to that are understanding from research that result in engineering innovations (Table 1), process control and cost-effective use of key inputs such as raw materials (malt), energy (cost, CO_2 emissions), water (and wastewater), and labour while minimising losses. A comprehensive review of the impact of innovation on brewing efficiency over a 30+ year period was reported by Pajunen and Hummer (2007). This is summarised in Table 5 which shows that labour efficiency increased 1600%, while water, and energy consumption were reduced by 20% and 50%, respectively.

It is currently fashionable to measure energy usage and efficiency in terms of greenhouse emissions (CO_2). One popular method for accounting for CO_2 and other greenhouse emissions is articulated by the Greenhouse Gas Protocol (Greenhouse Gas Protocol 2024) which divides emissions into Scope 1 (direct, gas use in kilning, etc.), Scope 2 (indirect, purchased inputs, etc.) and Scope 3 (indirect, use of product, etc.). A useful overview of malting from this perspective is provided by Davies (2010, 2020, 2023). This includes holistic lifecycle assessments that seek to enable calculation of the overall environmental impact of the product (malt). However, these conventions are yet to become universal, and they include assumptions and political compromises. As such, for the purposes of this review, energy efficiency is measured in SI units for energy rather than greenhouse gas emissions (CO_2).

The efficiency of malting has shown substantive improvements. In this CO_2 constrained era, most energy usage (heat) is during kilning (80-90%), both in terms of electricity (fans, pumps, turners, transfers) and heat energy (Tables 4, 6 and Figures 3, 4). The Danish Malting Group (2015) has calculated that it reduced energy use by 32.2% in its malt houses in Denmark and Poland between 1997-2014 (Figure 4). Correspondingly, Muntons Malt (2021) calculated that between 2010 and 2020, it reduced its 'carbon' footprint (energy use) by 38.5% in terms of CO_2 emissions per tonne of malt produced. These improvements in energy usage have been achieved by a combination of kiln design, heat recovery, lower kiln cast malt moisture and kiln temperature program. In addition, maltsters over the years have gradually sought to reduce the time frame of malting to achieve an ideal schedule of one day steeping, three to four days germination and one day kilning (Table 3) by using improved varieties and where permitted, GA. The burning of gas for heating of kilns is currently considered the most practical and efficient form of kiln temperature management. Recently, New Holland maltings commissioned a '100% emission-free' malt house at Eemshaven, in the Netherlands (Biogradlija 2024).

This plant aims to use 'emission-free' electricity to power all electrical processes in the plant (turning, transfer, fans, cleaning etc.) as well as shifting from gas fired kilning to electrically produced heat.

Table 4.

Malt house energy consumption between malthouses in Europe, Russia, China and Australia.

Total malting process consumption	Danish Malting Group[1]		Other companies[1]	
	Denmark	Poland	Russia	China
Electricity (kWh/t)	83	77	130	124
Heat (gas kWh/t)	571	665	670	1066
Water (m^3/t)	1.6	4.4	3.7	6.8
	Viterra (Joe White Maltings Australia)[2]			
Malting (excl. Kilning)	Port Adelaide[3]	Tamworth[4]	Perth[5]	
Electricity (kWh/t)	86	94	55	
Heat (gas kWh/t)	10	11	7	
Water (m^3/t)	n/a	n/a	n/a	
Kilning only				
Electricity (kWh/t)	70	77	45	
Heat (kWh/t)	1033	1094	706	

It is assumed that gas is providing most of the heat.
Extracted from [1] Danish Malting Group (2015) and [2] Stewart (2010).
[3] Port Adelaide (40% drum, 60% Saladin box, commissioned c1970s)
[4] Tamworth (50% drum, 50% Saladin box, commissioned c1970s)
[5] Perth (Modern circular, commissioned 2008)

The other primary use of energy pre-brewing is in the cultivation of malting barley, specifically the application of nitrogen fertiliser to support grain yield and protein levels. Higher levels of grain nitrogen are positively correlated with higher levels of foam promoting proteins and *beta*-amylase (DP), but negatively correlated with extract, flavour and protein modification (Evans et al. 2023). In terms of grain yield, the amount of nitrogen application is a function of the soil moisture. In general, Canada tends to have higher rates of nitrogen use than Australia due to the retention of greater soil moisture (deeper soils) and more reliable rainfall (Anbessa and Juskiw 2012).

The grain growers pay off for greater nitrogen fertiliser use and soil moisture results in higher grain yields. Conversely, in Australia, there is a finer balance between nitrogen and water availability as rainfall is more variable and less consistent compared to Canada, and the generally shallower depth of the Australian soil (Sadras et al 2016). Therefore, the risk for growers is if they do not get the balance between nitrogen fertilisation and water availability with variety, nitrogen use may be wrong resulting in potential losses in yield.

Table 5.

Impact of innovation during the last 30 years on brewing efficiency (from Pajunen and Hummer 2007).

Brewing efficiency parameters	Units	1960/1970's	2000+	Efficiency improvement/change
Malt use	kg/HL	~20	<15	~75%
Brews	N°/line/d	4-6	>12	~240
Brew volume	HL	300-400	>1,000	~285%
Lautering	h	>4	<2	~50%
Wort gravity	°P	12-13	18	~144%
Beer production time	Weeks	6-10	1-3	~25%
Water consumption	L/L beer	<20	~3-5	~20%
Labour Efficiency	HL/FTEE/yr	~6,000	100,000	~1600%
Energy consumption	MJ/HL	~200	~100	~50%
Filling line speed	per h	20,000	120,000	600%
Losses	%	~10	<2	~20%

A high barley GPC can result in 'haying off' (van Herwaarden et al 1998b), which can result in reduced yields in wheat of 34-50% (van Herwaarden et al 1998a). Haying off is a term that 'describes the premature ripening of cereal crops in conditions of high soil nitrogen and post anthesis drought' (Colwell 1963). Interestingly, the higher protein content of Canadian compared to Australia barley appears to be, at least in part, a function of photoperiod (terroir) during grain maturation (Evans et al. 2023).

It has long been assumed that the predominant energy usage in the production of barley is for nitrogen fertiliser and that this is comparable with that used for kilning. The main industrial procedure for production of nitrogen fertiliser is the early 20th Century Haber-Bosch process where atmospheric nitrogen is converted into ammonia using large amounts of electricity. Nitrogen fertiliser requires 7,760-11,111 kWh/t (or 30-42 GJ/t N, where 1 GJ = 277.78 kWh), with the electricity typically being sourced from fossil fuels (Wang et al. 2018; Ghavam et al. 2021; Brightling 2018).

Table 7 shows that when the nitrogen fertilisation rate and barley yield is considered, energy use for nitrogen is approximately 84-377 kWh/t on average compared to 600-1000 kWh/t for malting depending on the malthouse (Tables 4, 6; Figure 4). Accordingly, the energy cost for barley nitrogen fertilisation is less the 50% of the energy (median estimate 20-30%) used during malting (primarily

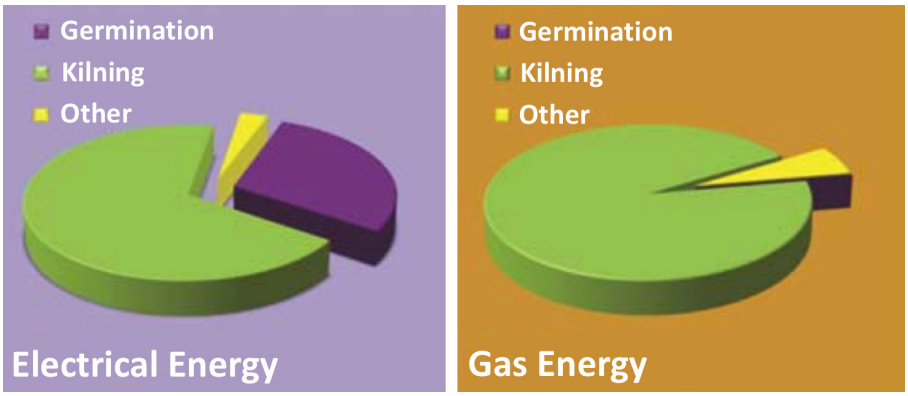

Figure 3.

Energy useage in malting (Davies 2010). For both electrical and gas energy, the prime area of usage is kilning due to fan and heating requirements. For germination the most significant area is electrical energy. Reproduced with permission of the author.

Figure 4.

Average energy consumption for both electrical and gas energy during malting in Denmark and Poland between 1997 to 2014 (Danish Malting Group 2015). Reproduced with permission of the Viking Malt Group, Denmark.

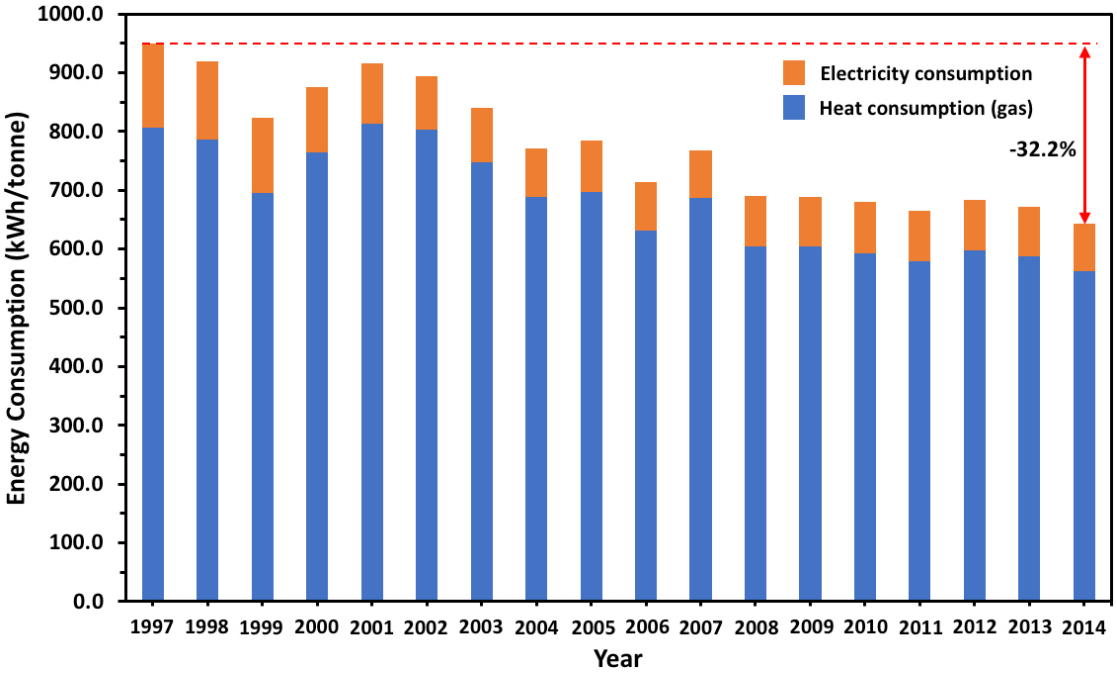

Table 6.

Energy inputs in modern malting

Malting stage	Energy Input	Amount (KWh/tonne)
Steeping and Germination	Electricity	13.9
	Process fuel (gas)	66.7
Kilning	Electricity	83.3
	Process fuel (gas)	677.1
Malt total energy	Electricity	97.2
	Process fuel (gas)	743.8
	Total Energy	841.0

Adapted from Brookes (1993).

Conversion from GJ/tonne to kWh/tonne by multiplication with 277.778

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kilning). However, based on CO_2 emissions, it is likely that energy use is towards the higher estimate in rainfall plentiful countries like the UK were nitrogen fertiliser use is higher (Davies 2023). In some growing regions (UK, Northern Europe), agronomic practices for barley require an extra energy cost to dry the barley from ~16% moisture to ~12% moisture to enable safe storage of barley. It has been estimated that the energy cost of barley drying cost in the UK was 9-10% (Davies 2023) of that used during malting or ~84kWh/t (Table 6).

Improvements in the efficiency of malting (and brewing) processes ensures that primary products (beer and whisky), are more affordable. Unfortunately, this has attracted the interest of Royalty and politicians who have levied taxes and added bureaucratic constraints to ensure these taxes are paid. Perhaps the most famous of these tax laws is the Reinheitsgebot or 'German purity law' of 1516 which to this day limits German brewers to using only barley malt, hops and water, with yeast considered a fixture of the brewing process (Oliver 2011).

Table 7.

Estimation of nitrogen fertiliser use for dry land barley production in Alberta, Western Canada and Western Australia.

Geographic region	Yield (Av. t/ha)	N application (Av. kg/ha)	Estimated N fertiliser energy equivalents	
			Low (kWh/t)[1]	High (kWh/t)[1]
Alberta, Canada (2005 - 14)	3.46[2]	57[2]	128	192
Western Canada (2012 - 22)[3]				
(A) N follow fallow or legume	3.13	34	84	127
(B) N follow grass and grass-legume	3.13	62	154	231
(C) N follow stubble	3.13	101	250	377
Western Australia (2012 - 22)	3.03[4]	37[5]	95	143
Australia (average c 2017)	2.30[6]	45[7]	152	228

[1] Nitrogen fertiliser manufacture requires Low: 7,760 – high: 11,000 kWh/t (Wang et al. 2018; Brightling 2018; Ghavam et al. 2021),
[2] Chapagain and Good (2015),
[3] Data provided by Yueshu Li, CMBTC, general nitrogen applications as follows: (A) 0-34 kg/ha nitrogen following fallow or legume breaking, (B) 34-62 kg/ha nitrogen following grass and grass-legume break, and (C) 62-101 kg/ha nitrogen following stubble.
[4] GIWA (2023),
[5] Harries et al (2021) average nitrogen for dry land cereal production 2010-2014,
[6] Consensus figure surveyed from Australian Agronomists and barley breeders by D.E. Evans 2023.,
[7] Angus and Grace (2017).

With respect to malting from 1300 to 1875, Stopes (1885) makes it is abundantly clear that the production of malt is indelibly linked with taxation and regulation. The Scottish poet, Robert Burns, in 'The Earnest Cry and Prayer' (1786) versed a plea against increased duties on whisky.

'Ye Irish lords, ye knights an' squires,
Wha represent our brughs an' shires,
An' doucely manage our affairs
In parliament, …….
Freedom and whisky gang the gither,
Tak aff your dram!'

Between barley growing and brewing comes malting, which represents *'the middle parts of fortune'* (Frederick Manning, 1929 - itself a paraphrase from Shakespeare's 'Hamlet'). Within this, the efficiency of malting has steadily improved over time. During steeping, substantial volumes of water are used (and discharged), while during kilning, large amounts of energy are used to dry the green malt from 44-46% moisture to kilned malt with 4-6% moisture. Boortmalt, the world's largest maltster (~3 million tonnes pa) has reported (Michiel Jorissen, personal communication) its ambition by 2030 to reduce water usage by 50% and energy usage by 60% of that used in 2010. This is to be achieved while producing malt meeting the Congress-EBC specifications for protein, fine extract, modification (Kolbach index), diastatic power, wort viscosity, FAN (O'Rourke 2002). A handy interpretation of these measures of malt quality can be found in Yin (2021).

This review considers the status of malting to identify process objectives to improve efficiency in terms of water, energy and use of labour to improve the quality and homogeneity of malt to enable progress in sustainability and profitability.

Barley selection

There is an age-old truism that, 'you can't make a silk purse out of a sow's ear.' This is the case with malting barley, where high quality barley from the most suitable varieties is sought by maltsters to make malt. Such barley, that has been grown under the most suitable conditions, will malt most efficiently to a quality that meets expectations of the brewer. However, occasional suboptimal barley growing conditions, such as droughts, can result in higher protein content (van Herwaarden et al. 1998 a,b; Luo et al. 2019; Halstead et al. 2023).

There is also the subtle question of the influence of 'terroir' (Evans et al. 2023) which has received greater scrutiny as a challenge and opportunity to consistently make high quality malt despite the climate challenges of different geographic locations.

Maltsters are innovative and have developed strategies to cope with such variabilities. Indeed, maltsters select pure varietal parcels of barley for malting as different varieties perform differently during malting. Chinese maltsters have applied such criteria to take advantage of lower cost and quality with FAQ (Fair Average Quality) selections of barley (malting varieties) to surprisingly make high quality malt (Evans et al. 2022).

A. Barley selection: barley germinability, physical size, storage and drying

In defining barley suitability for malting there are a triumvirate of key characters: (i) germinability, (ii) dormancy and (iii) grain protein content (GPC). To make high quality malt, maltsters must purchase and use barley that is able to germinate. The minimum acceptable level of barley germinability is >95% (Bason et al. 1993; Kunze 1999; Yin 2021; MAGB 2023). Further maltsters actively avoid barley parcels with excessive levels of broken grains skinned (husk), small or weather damaged grain (preharvest rain sprouting), that are all factors which would reduce germinability (Briggs 1978). In the UK, maltsters ensure that ≥98% of corns are >2.2mm so that grains are plump for consistent water uptake and modification. Where possible the barley should be free of field fungal infections (Bretträger et al. 2023), including *Fusarium* head blight/scab that can result in undesirable levels of mycotoxins (e.g., DON - deoxynivalenol) and the potential of the beer to 'gush' or over foam on opening the bottle or can (Schwarz and Han 2003; Garbe et al. 2009).

Once the barley crop has been harvested the barley must be stored, then potentially transported significant distances to the malting plant. A factor in barley storage is the level of grain moisture which can range from <12% to 25% (Kunze 2004), depending on the growing region and the season (rain and humidity).

It is however critical that the level of grain moisture for storage is below 14% moisture to ensure germinative capacity. Moisture contents above 14% can promote insect infections and during storage, microbial growth can produce mycotoxins (e.g., ochratoxin A - Flannigan 2003; Albini et al. 2018; Martynov et al. 2018).

Where the moisture of harvested barley is >14% the barley will need to be quickly dried after harvest, with air or heat assistance, to avoid the loss of vigour/ germination and insect or microbial infection. A high barley moisture content will also potentially increase transportation costs and malting losses (Table 2). In some areas, such as the UK, Scandinavia Baltic states and the Russian Federation, barley drying is required in most seasons (Bishop 1944, Gordon 1968; Martynov et al. 2018; MAGB 2023), while in other areas, such as North America, the use of barley drying is more occasional (Wilcke and Hellevang 1992; Albini et al. 2018). Barley moisture in the UK and Ireland can be as high as 16-18%. In contrast, the Australian barley crop is very rarely if ever dried due to the hot and dry conditions at harvest resulting in a grain moisture on average of 11.2% (range 8.6-14.3%, Woonton et al. 2005, Evans et al. 2014).

Barley drying comes at an energy cost. It has been estimated that the cost of barley drying is 9-10% of energy use during malting or ~84 kWh/t (Table 6). Martynov et al (2018) reported that conventional grain dryers use up to 6 MJ/kg of each percentage point of evaporated moisture. Employing heat recovery equipment and protocols can reduce the thermal usage by up to 75% (Sorochinsky 2011). In addition to heat recovery, other energy conserving drying technologies are being explored, such as vacuum - infrared drying (Martynov et al. 2018) and air flow reversal during fixed bed drying (Albini et al. 2018). It follows that geographical areas that do not or rarely require barley drying have an advantage with respect to energy usage.

Storage temperatures around 15°C, should be reached as soon as possible after harvest and drying, to reduce insect infection and maintain the germinative vigour of the barley (Caddick and Shelton 1998). Short periods of higher temperatures (30-40°C) can be applied to enable to break barley dormancy.

B. Barley selection: dormancy

Commercial maltsters understand that different varieties can malt differently. In the main, these experiences are largely related to barley dormancy. Maltsters observe two types of dormancy.

1. Primary dormancy – dormancy up to and for a period after harvest.
2. Secondary dormancy – later onset dormancy due to prolonged heating (>30°C) and/or prolonged storage.

Primary dormancy in the field until barley storage, is often of benefit to grain growers and maltsters since it precludes preharvest sprouting (which reduces germinability) as a result of preharvest rainfall (Jacobsen et al. 2002). Primary dormancy is largely due to the balance of abscisic acid (ABA) and gibberellic acid (GA), (Finch-Savage and Leubner-Metzger 2006; Finkelstein et al. 2008), along with temperature and rainfall (Mares 1987, Caddick and Shelton 1998). However, Jacobsen et al (2002) contends that abscisic acid is the primary effector of dormancy, with respect to the rate of its catabolism after ripening, determining when dormancy is broken after harvest.

Figure 5 shows the impact of exogenous GA addition on malt quality and dormancy with Australian grown barley (grown 2006) that were micro-malted 'early season' in 2007 (Evans et al. 2009). Australian malting barley varieties are recognised as having low barley dormancy due to the dry and hot harvest conditions. As such with Australian barley, the impacts of dormancy will be subtle. Many maltsters will evaluate the malting of new season barley by early season micro-malting trials with and without GA. Such information is critical for the malting season programming for use of these barley supplies.

Figure 5 also shows the malting outcome for several malt quality parameters that are impacted by barley dormancy and promoted by GA. These include malting protein and Kolbach index (KI), endo-proteases (Jones 2005), and the two GA responsive DP enzymes, α-amylase and limit dextrinase (LD), and β-glucanase (Hardie 1975, Evans et al. 2009). Although *beta*-amylase was also measured, it was not responsive to GA as expected (Hardie 1975)

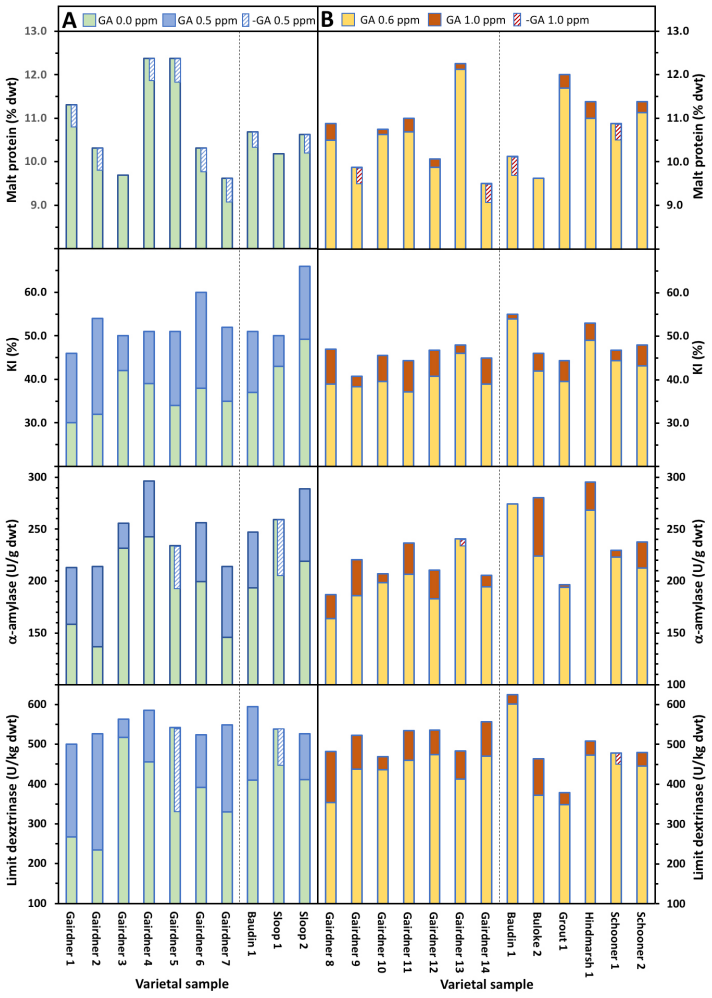
and consequently showed little variation with GA addition (Evans et al. 2009). Small differences in malt protein are evident for the paired samples in Figure 5 with a small decrease in barley to malt protein evident with the addition of 0.5 mg/L GA (% GA effect: mean = -3.1%, standard deviation = 2.4%), but less of a decrease, and in some cases an increase comparing 0.6 with 1.0 mg/L GA addition (mean = -0.5%, standard deviation = 2.7 %).

Malting is understood to result in small differences between barley and malt protein contents (Yousif and Evans 2020) but with substantial changes in the 'Osborne' protein fractions during malting (Osborne 1924, Folkes and Yemm 1958). With all paired samples, the Kolbach index (KI) was promoted (mean = 37.0%, standard deviation = 20.8%) by 0.5 mg/L GA, although muted when increased from 0.6 to 1.0 mg/L GA (mean = 10.1%, standard deviation = 6.6%). For both α-amylase and LD there were variable but generally substantial responses to 0.5 g/L GA (mean = 20.9%, standard deviation = 23.0%, and mean = 36.3%, standard deviation = 48.4%). Like KI, increasing GA from 0.6 to 1.0 g/L did not have as great an impact as 0.5 g/L for α-amylase (mean = 8.3%, standard deviation = 8.6%) and LD (mean = 13.7%, standard deviation = 9.5%). It was noted that in some malted samples, the response to GA was less than the control (Gairdner 5, Sloop 1) for α-amylase and LD. Similarly, several varietal samples exhibited small decreases in malt protein levels particularly for the 0.0 to 0.5 g/L GA comparison. This was presumably indicative of the complex balance between starch, cell wall polysaccharide and protein hydrolysis (Yousif and Evans 2020).

Overall, Figure 5 demonstrates that there is significant variation in the response of germinated barley to GA within and between varietal samples. In part, this is the result of lingering vestiges of dormancy. The adage that there is as much variation within varieties as between varieties is largely confirmed by this data. It shows why maltsters, if allowed by their customers, will select the appropriate variety and use GA to efficiently achieve malting outcomes that meet specifications, particularly with new season malt. Figure 5 also highlights the impact of dormancy and varietal variability that result from differences in growing conditions such as temperature and rainfall (Mares 1987; Caddick and Shelton 1998).

Figure 5.

The influence of exogenous gibberelic acid (GA3) application during micro-malting on samples of Gairdner from different sites, grown in 2006. A. Paired barley samples with 0 and 0.6 mg/L GA3; B. Paired barley samples with 0.5 and 1.0 mg/L GA3. GA3 0.6 (A) and 1.0 (B) mg/L with values less than GA 0.0 (A) and GA 0.6 (B) mg/L respectively, represented as indented hatched bars. LSD (P<0.05) for the measurements were: total limit dextrinase = 29, α-amylase = 8. KI and protein were not available. Figure from unpublished data (Evans and Nischwitz) and Evans et al (2009).



Beyond the partial mediation of dormancy by GA, maltsters have other options. For example, the selection of varieties that have lower levels of dormancy, although this strategy needs to be calibrated by maltsters and barley growers against the risk of preharvest sprouting (Jacobsen et al, 2002). For instance, even in barley growing environments in Australia where harvest conditions are typically hot and dry, wet harvests can occur – for example in 2014 – resulting in the problem of preharvest sprouting. On this occasion, the

Australian variety Flagship, which has very little dormancy, resulted in significant losses and down degrading from the malting pool due to preharvest sprouting. As such, maltsters need to adopt barley intake strategies to cope with at least some level of barley dormancy.

There are several non-GA based options for maltsters to overcome dormancy. The simplest and most passive method is to store the barley at 12-15°C until dormancy has abated. Given that most commercial maltings operate 24/7, 365 days a year, this passive strategy poses a problem during the early stages of the new malting season. A more proactive approach is to store barley for a short period at 20–35°C (Bishop 1944; Pollock 1962; Gordon 1968; Briggs 1981, 1994; Caddick and Shelton 1998; Reuss et al. 2003). However, care is required in that the duration of heating is not too long at > 35°C (Bishop 1944; Aastrup et al. 1989; Briggs et al. 1994), presumably because the enzymes that catabolise ABA (Jacobsen et al. 2002; Woonton et al. 2005; Millar et al. 2006) are progressively inactivated. Leymarie et al (2008) observed that heating at 30°C for 24-48 hours could invoke a substantial secondary dormancy via less ABA catabolism which further reinforces that heat treatments to break dormancy should not be overdone. It has also been shown that nitric oxide (NO) can break the dormancy of barley grains (Bethke et al. 2004). Nitric oxide and other plant gazo-transmitters (CO, H_2S, CH_4, H_2) appear to modulate plant phytohormone levels (auxin, ABA, GA) with positive effects on seed germination and plant growth (Liu et al. 2007; Wang 2014; Li et al. 2021; Wang et al. 2022). It should be noted that NO and other gazo-transmitters can be hazardous to human health beyond threshold concentrations. Bishop (1944) outlines several other potential treatments for breaking dormancy including cold treatment, lime water, sulphuric acid, calcium hypochlorite, hydrogen peroxide, ethylene and acetylene. However, none of these options are currently used commercially for breaking dormancy.

A parallel component of dormancy is water sensitivity which can be a factor in the ability of the grain to germinate (Gordon 1968). Crabb and Kirsop (1969) defined water sensitivity to be a 'reflection of a higher oxygen requirement for germination of the embryo.' This would be potentially modulated by the microflora on the grain. The development of the barley water sensitivity test resulted in the well known 4 and 8 ml barley water-sensitivity test (Essery et al 1955). After the first steep, water sensitivity can be a problem in the UK, in controlling barley moisture to be no greater than 32%. The subsequent dry rest allows the surface moisture to be taken up before germination begins.

Secondary dormancy is a common occurrence in the seeds of species where after primary dormancy dissipates, dormancy develops in seeds where germination is again inhibited (Karsen 1980; Hilhorst 2007; Leymarie et al. 2008). Here, 'secondary dormancy' can be extended to include a slowness to germinate because of lengthy grain storage or ageing. Maltsters often encounter this, with varietal variation towards the end of the malting season. Often the barley will be described as being 'sluggish' to germinate and modify (Sychra et al. 2001). Where permitted, the application of exogenous GA can assist the germination and modification of older season malting barley. Ishibashi et al. (2015) observed that reactive oxygen species (ROS) produced by NADPH oxidases in the embryo and aleurone cells can promote germination while antioxidants can supress it. Conversely, Kranner and Birtic (2005) attributes the inhibition of germination to the gradual accumulation of free radicles during storage.

In plant breeding programs, it has been found that with very old seeds, germination can be stimulated by inclusion of a reducing agent such as 0.5% thiourea on lettuce seeds (Thompson and Kosar, 1938) or vetch (*Vicia sativa* L. Rathjen 1997). Interestingly, a potential accelerator of malt germination and modification, hydrogen (applied as hydrogen enriched water, HRW, Li et al. 2021), is a weak-moderate reductant (reduction potential (V) = 0.00, Silberberg et al (2006). Certainly Ohsawa et al (2007) has observed that H_2 is capable of neutralising cytotoxic reactive oxygen species (ROS) such as the hydroxyl radical (•OH) and peroxynitrite anion (ONOO-). Therefore, the agency of H_2 as a reductant could potentially alleviate secondary dormancy because of storage.

C. Barley selection: protein and other components

The third member of the triumvirate defining the suitability of barley for malting is protein. In Australia the typical acceptable range of grain protein content (GPC) range for premium Malt 1 is typically 9-12.0%, while in North America and Canada, the range for malting barley is 10-13% (Evans et al. 2023). A minimum level of protein in malt is critical to achieve a satisfactory free amino nitrogen (FAN) range in wort with a minimum of 100 mg/L and a maximum of 220mg/L being required to support yeast nutrition during fermentation (Hammond, 2000). Higher levels of FAN are required to be contributed by malt when used with unmalted adjuncts (rice or corn) and sugar syrups which 'dilute' the FAN (Meilgaard 1976; O'Rourke 1999). A practically useful prediction of the relationship between GPC and FAN has been found and exploited to assist in the procurement of barley for malting (Axcell 2018). The 'Axcell equation'

$$TN = FAN/(2.3 \times KI)$$

can be used to estimate the levels of barley nitrogen required to produce malt with greater than the minimum FAN within the satisfactory range of the Kolbach index (KI). It follows that barley/malt with higher GPC at similar levels of protein modification (typical malt specification KI = 39-45%) will result in higher FAN levels which is of value when using non-malted starch adjuncts or sugar syrups.

Malt quality relationships with protein extend beyond FAN (Evans et al 2023), with relationships that are (1) Positive: *beta*-amylase (diastatic power), foam positive proteins (protein Z4, hordeins) or (2) Negative: extract, KI, complexity of wort flavour complexity and intensity.

Of these GPC relationships, the Kolbach index (KI) is especially worthy of further consideration. Firstly, Evans et al (2023) reported that both crop nitrogen fertilisation rate and terroir influenced the composition and proportion of albumins/globulins and hordeins. In comparing in 2014, the Walebing site (Western Australia) with the Lancombe site (Alberta, Canada), it was observed at the Canadian site that the Australian varieties (Buloke and Commander) had reduced proportions of albumins/globulins and increased total hordeins with respect to the Canadian varieties (Bentley and CDC Meredith). Within the hordeins, the proportion of C hordein increased while B hordein decreased, particularly for the variety Commander. Such changes in protein composition could potentially alter the propensity of grain protein to modify (KI) and also the composition of amino acids released (FAN), with potential implications for fermentation (Donhauser and Wagner 1990; Edney and Langrell 2005; Gibson et al. 2009; Yin et al. 2017).

A wider micro-malting trial was conducted that assessed the interaction between GPC and protein modification (KI, Figure 6). The barley was grown at three sites in 2013-2014, two in Western Australia and one in Canada at varying levels of nitogen fertilisation with two Australian and two Canadian barley varieties (Luo et al. 2019; Evans et al. 2023). All samples were malted using the same micro-malting protocol and equipment (Joe White Micro-Malter, Perth, Australia). It is acknowledged that, in a commercial malting, the maltster would subtly modify steeping and germination conditions to ameliorate malt quality, particularly with respect to ensuring the Kolbach index remains within customer specifications. Figure 6 shows GPC and KI data with respect to variety, growing season and site which showed an overall correlation of $r = -0.473$ ($P < 0.01$). Surprisingly, variety, growing season and location resulted in an increase in the GPC versus KI correlations ($r = -0.969$ to -0.637, $P < 0.05$). Seasonal effects were observed in the GPC versus KI relationship such with the Australian Cunderdin site in 2013 compared to the Walebing site in 2012/14 for Buloke/Commander, and the difference for the Australian grown Meredith/Bentley compared to Buloke/Commander. In addition, Luo et al (2019) commented that Canadian grown barley was slower to modify protein. The greater proportion of hordein compared to albumin/globulin with the Lacombe site (Canada) grown barley may at least partially explain this observation. With respect to differences in Canadian-Australian production, more predictive inverse relationships were found between GPC and KI when variety, and growing season (presumably terroir) were considered. Also, in addition to the protein to KI relationship, there may also be a relationship between KI and the key proteinases which respond to gibberellic acid (Mikola 1987; Wallace et al. 1988; Jones 2005; Evans et al. 2009).

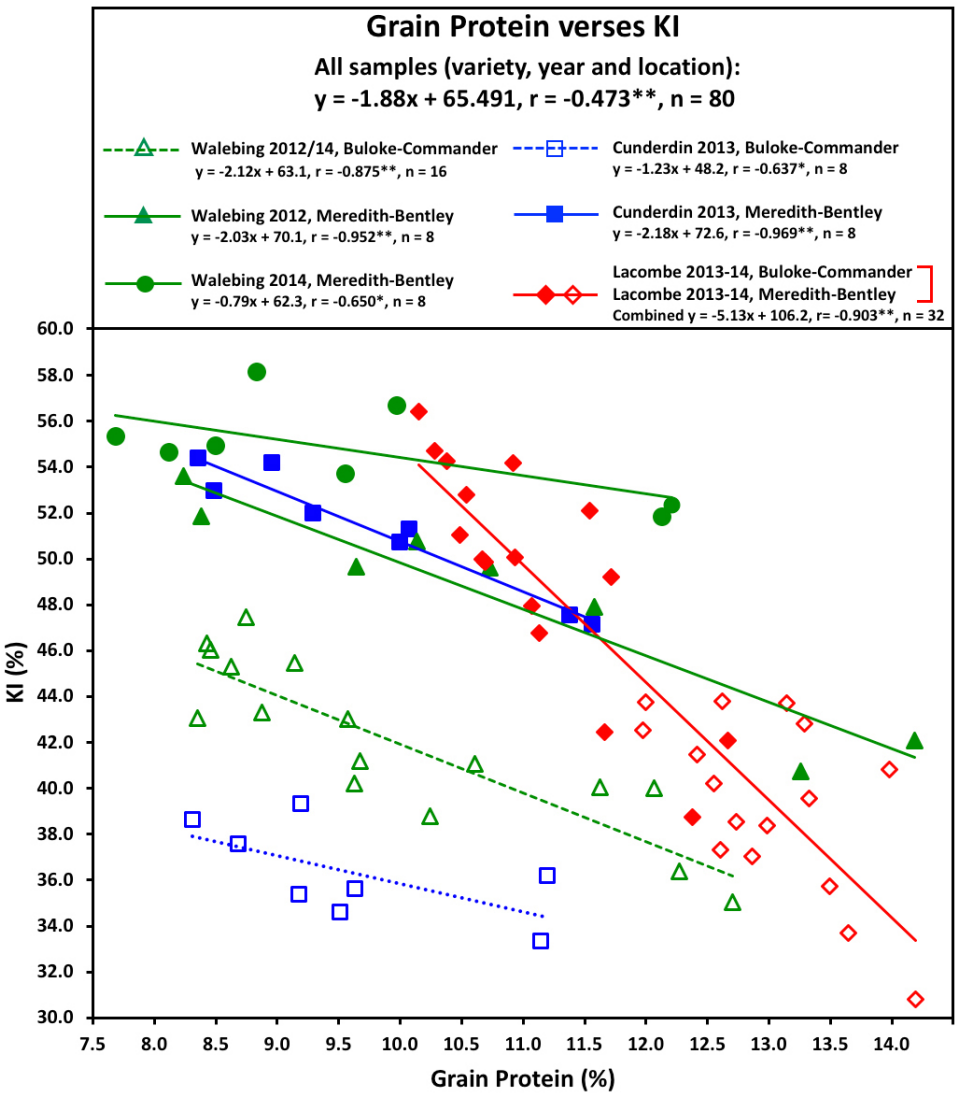


Figure 6.

Relationship between grain protein and Kolbach index (KI) for malt produced from barley grown in Western Australia (Cunderdin - 2013 and Walebing sites – 2012/14) or Canada (Lacombe site 2013/14) using two mainstream Australian (Buloke, Commander) and Canadian (Bentley, Meredith) barley varieties in the 2012 to 2014 growing seasons, * = P < 0.05, ** = P < 0.01. Unpublished data from Luo et al (2019).

Maltsters also need to contend with variation of malt protein content within a barley piece. One way maltsters control the GPC variation of barley is to malt only plump grains (e.g., >2.5mm, Magliano et al. 2014), as grains of more consistent size tend to imbibe and modify more evenly. A novel approach was taken by Sheehy et al (2009) to use a NIR-based grain sorter (Model TriQ 20, BoMill AB, Sweden) for single grains (Muller-Aufferman and Jacob, 2014). Table 8 shows five fractions that were separated from a composite sample of malting barley, where the minimum GPC was 8.4% and the maximum was 13.4%. Barley fractions with lower protein contents (like Figure 6), showed higher levels of modification (Kolbach index), while higher protein content fractions showed progressive decreases in KI. Interestingly, this pattern was replicated with lower protein fractions producing higher extract but lower wort viscosity and β-glucan content, compared to higher protein samples. Stewart et al (2023) also observed that wort made from barley with lower protein content and higher modification had greater flavour complexity/intensity. Combined these observations suggests that maltsters should pay attention to the geographical region that their malting barley is sourced (terroir) and its protein content. Further, barley should preferably be as homogenous as practicable and, where possible, stored or sorted before malting into tight bands of protein content. Barley malted in this way should more easily fit to customer specifications and increase satisfaction.

Parallel modification of barley components (other than protein) can impact the brewing efficiency of malted barley. The modification of starch granules has been linked with to the ease of starch gelatinisation; a requirement for efficient starch hydrolysis by DP enzymes during mashing (Ramanan et al. 2023). It remains to be determined which endosperm component, presumably protein, is responsible for these modifications in starch gelation. It has also been observed that there is an interaction between β-glucan content and environmental barley growing

Table 8.

Protein and micro-malting results for a composite sample and five fractions fractionated by a NIR grain sorter (Model TriQ 20, BoMill AB, Sweden). Data from Sheehy et al (2009).

Sample	Barley moisture (%)	Total barley protein (% Dwt, NIR)			Malt quality			
		Av.	Max.	Mini.	Extract Fine (%)	KI (%)	Viscosity, wort (cP)[1]	β-Glucan, wort (mg/L)[1]
Composite	11.1	10.8	11.4	10.2	79.5	32.0	1.54	124
Fraction 1	11.0	9.0	9.5	8.4	81.3	37.4	1.52	82
Fraction 2	10.8	10.1	10.7	9.7	80.5	33.4	1.53	96
Fraction 3	10.8	11.1	11.7	10.4	79.1	33.3	1.68	119
Fraction 4	10.7	12.1	12.9	11.6	78.7	29.3	1.62	194
Fraction 5	10.7	12.6	13.4	12.0	78.2	30.0	nd	nd

[1] Separate micro-malting of the same barley sample, nd ⊨ not determined

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D: Barley selection: hulless barley

The husk component of a barley grain comprises approximately 7-13% of grain weight (Whitmore 1960; Evers et al. 1999). Lower proportions of barley husk and low hull adherence can result in husk damage and losses during handling and transport of both barley and malt (Olkku et al. 2005). This can cause practical issues for both maltsters and brewers (in silo classification). As the husk is primarily composed of cellulose, hemicellulose and lignin (Olkku et al. 2005), it offers little or nothing to wort and its subsequent fermentation. For conventional brewing (mash separation by lauter tun), it is convention that at least ~50% of the grist bill is comprised of husked malt to form an adequate

lautering bed to produce bright wort (Kunze 1999; Briggs 2004). The advent of the modern Meura mash filter, suggested that hulless barley could comprise 100% of the grist if finely hammer milled (van Waesberghe 1991; Melis 1993; Buhler 1995; Wackerbauer 1996) and the husk would not be required for mash separation. The absence of the barley husk potentially enables an enticing 5-8% increase in extract at pilot scale (Evans et al. 1999; Rossnagel 1999; Izydorczyk et al. 2023; McCaig et al. 2006; Li et al. 2023). Brewing trials with hulless malt showed a small reduction in mash filtration efficiency which were not insurmountable (Stewart et al. 2004; McCaig et al. 2006; Li et al. 2023). Evans et al (1999) observed that a small amount of husk (<20%) resulted in some improvement in mash filter performance. Given that, with hulless barley a proportion of the grains (<10%) are covered by husk this - in practice - is not an issue.

The use of hulless barley presents several opportunities. Firstly, hulless barley is more efficient for malting, storage and transport due to the loss of ~11% (on average) of grain weight. Further, the transport of a tonne of hulless barley will occupy a third less space (Armstrong 2023). In addition, in malting there would be shorter steeping times and lower steep leaching losses since the rough surface of the husk traps dirt (Bhatty 1996). During brewing, the absence of husk and the higher extract would result in a reduced volume of spent grain. Beer flavour (astringency) and flavour stability may benefit due to the absence of the husk (Prechtl 1967; van Waesberghe 1991; Cortés et al. 2010; Nishida et al. 2005; Zhang et al. 2019). The absence of the husk would also likely reduce the risk of premature yeast flocculation (van Nierop et al. 2006; Lake and Speers 2008: Evans and Kaur 2009) which is proposed to be caused by the xylanase release of arabinoxylan from the husk (Herrera and Axcell 1991 a,b; van Nierop et al. 2004; Koizumi et al. 2008; 2009; Shang et al. 2014, 2020; Xie et al. 2022).

There are several significant challenges with hulless barley that maltsters need to develop processes to overcome. Foremost is the germ on hulless barley is not protected by the husk (McCaig et al. 2006) which requires the handling equipment during harvest, storage and malting to avoid undesirable reductions in germinability potentially leading to lower malt homogeneity, lower modification and higher wort β-glucan.

These qualities may predispose beer made from hulless barley to produce hazes (Li et al 2023). Indeed many hulless barley varieties produce malt with intrinsically high β-glucan levels, although varieties with reduced levels have been developed (McCaig et al. 2006; Izydorczyk et al. 2023). With germination and kilning, the absence of husk redefines the dynamics of airflow around the grain in the bed (St. Johnston 1954) requiring an adjustment of conventional malting practice.

During kilning, the absence of the husk accentuates what Thomas (1986) described as the 'case hardening' effect (identified with a friabilimeter) where the outer layer of the corn is hardened by heat applied to protein and starch in the less well protected outer grain layers (aleurone layer, endosperm). With commercial scale malting and brewing, case hardening (as with husked malt) is considered the cause of disappointing brewhouse yield (Stewart et al. 2004) relative to pilot scale brewing trials that indicated fine extract improvements of the order of 5-8% from hulless malt. In the future, commercial maltsters will need to continue to improve malting process management to achieve the promises in efficiency of hulless malt.

Improving steeping efficiency

Steeping is the most water intensive step of the malting process, using potable water for two to three wet steeps. The quantity of water used in steeping has been estimated for the more water efficient conical steeps at 0.8m^3/t and for flat bottom steeps at ~1.3m^3/t (Aalbers et al. 1983; Briggs 1998). In practical malting, the water consumption of flat bottom steeps is 1.23m3/t/wetting, so for a three steep programme this would equate to 3.69m^3/t. In comparison, a conical steep would use 0.8m^3/t/wetting and 2.40m^3/t for three wet periods. Water from the first steep has relatively high levels of dissolved components, microorganisms and organic matter that add cost for waste treatment and present challenges for discharge or recycling for subsequent steeping phases.

Care is required in the modification of steeping conditions as 'it has been recognised by maltsters for many years that the most important part of the malting process is the steeping. Failure to carry out this portion of the malting cycle correctly cannot be rectified during germination or kilning' (Axcell et al. 1984). A similar sentiment with regards to the importance of steeping was expressed by Aalbers et al (1983).

The objective of steeping is to rapidly increase the water content of barley from 10-13% to >40% (ideally 42-45%) to enable germination (Yin 2021). Brookes et al (1976) provides an excellent review of steeping, particularly to the rate of water up take which ensues germination, and how this is subsequently reflected in malt quality. The rate at which barley imbibes water appears to be related to the relationship between hydration and the physical structure of the kernel (Baker and Dick 1905; Collins 1918; Gruss 1930; Dickson and Burkhart 1942; Pollock 1962; Kirsop et al. 1967; Axcell et al. 1983; Davies 1991; Landau et al. 1996). Imbibing factors include seed morphology (micropyle, structure and the permeability of the seed coat, testa and pericarp), the ability of the endosperm to hydrate and the availability of water. Further, Landau et al (1996) found in Stirling barley (Australia) that the morphology of a channel running from the ventral scutellum to distal end of the grain was critical to the rate of hydration. Another key factor in the rate of barley hydration during steeping is the water temperature (Brookes et al. 1976). More recently, Mayolle et al (2012) provided further clarity on the diffusion of water through four different qualities of hydrating barley grains. Temperatures higher than the normal 12-16°C, will result in more rapid hydration with the consequence of undesirable aberrations during germination (Brookes et al. 1976; Briggs 1987). It can be concluded that the steeping regime of different varieties of barley is critical in terms of the length of immersion and air rests for steep out moisture and modulation of malt quality (Axcell et al. 1983; Turner et al. 2019).

A. Steeping efficiency – physical interventions

Abrasion or scarification of barley found favour in the United Kingdom during the 1970's/80's (Brookes 1980; Briggs 1987) which saved a day of the six to seven day malting process (Brookes 1980).

The pioneering work on abrasion by Palmer at the Brewing Research Foundation in the UK (Palmer 1969; Palmer et al. 1970) was influenced by earlier work (Sparrow 1964, 1965) on the application of GA to dehusked barley. Abrasion mechanically perforates the pericarp-testa of the grain to improve the rate and homogeneity of water uptake. Abrasion also enhances the response of the grain to GA and improve oxygen ingress to the grains modifying tissues (Briggs 1987). Preferably abrasion is effected at the distal (non-germ end) of the grain so as not to unduly damage the embryo or the husk for later lautering (Palmer 1969). With the advent of less dormant barley varieties and malting practices with shorter malting times, abrasion is now not in widespread use. However, it remains a technique that could be considered when looking to increase the rate and efficiency of malting.

B. Steeping efficiency: additives

Several steep additives that have been considered over the last century or so. These include potassium bromate for reducing malting losses, the addition of various agents to reduce the levels of microflora (lime water, hydrogen peroxide, ozone, sodium hypochlorite), novel factors (e.g., chitooligosacchride) and growth promoters (GA, potentially hydrogen). Briggs (1987) provides a useful overview of these topics. Bromate addition during steeping reduces rootlet growth and malting losses but has been discarded due to its inherent toxicity (oral LD_{50} 157mg/kg, ECHA) and its aquatic toxicity (EC_{50} >100mg/l, ECHA) which results in difficulties in steep water disposal (ECHA 2023). In recent years, investigators have trialled the addition of chitooligosacchride during steeping to prime the barley grain for malting (Lan et al. 2016). Interestingly the authors observed that the treatment resulted in elevated levels of hydrolases (α-/*beta*-amylase, proteinase, β-glucanase) and antioxidases (superoxide dismutase, catalase).

Growth promoters such as GA are malting additives that both stimulate barley germination and expedite malt modification to reduce malting times and improve malting efficiency (Palmer 1974; Brookes et al. 1976; Kunze 1999; Thomas 2014; Yin 2021). The first report of the growth and amylase promoting effect of GA was from Japan (Hayashi 1940). Almost twenty years later his countrymen Munekata and

Kato (1957) reported on the application of GA to the malting process. This was rapidly followed by reports from Sandegren and Beling (1959), Paleg (1960 a,b) and Macey and Stowell (1961) which ushered in the commercial use of GA in malting.

GA enables a more appropriate malting response of some barley varieties towards the end of the malting season. Such varieties are slow to malt due to the onset of secondary dormancy. GA can be applied by sprays (Thomas 2014), either during steeping (1-2 mg/kg barley) or during germination after chitting (0.1-0.2 mg/kg barley). Contemporary malting practices apply GA during the germination phase after chitting, as the germ is less likely to be damaged during steep transfer. Further, reduced quantities of GA are required which is cost attractive for maltsters.

As outlined above, the application of GA reduces the impact of barley dormancy, both primary and secondary. GA application accelerates grain modification, particularly in association with abrasion as it directly stimulates the synthesis in the aleurone of hydrolytic enzymes (α-amylase, β-glucanase, limit dextrinase, proteases (Hardie 1975) and indirectly with *beta*-amylase (Evans et al. 2009). Accordingly, it is surprising that GA is akin to 'the love that dares to speak its name' (Douglas 1894) in the brewing industry, whether the Reinheitsgebot (German Purity law, 1516) or brewing groups for marketing reasons. Gibberellin (typically GA_3) is essentially an 'organic' extract from fungi or bacteria (*Gibberella fujikuroi*, Jefferys 1970), so it is surprising that there is resistance to its use in the brewing industries. Interestingly, several 'GA free' (exogenous) brewers are reviewing their position, presumably towards reducing greenhouse emissions (CO_2) from the production chain.

One is to malt 'GA free' barley varieties that do not require application of exogenous GA during malting to efficiently achieve satisfactory malt quality. In recent years it has been recognised by maltsters that different varieties have differing abilities to respond to GA. Yet, published reports that identify such varieties, and their performance are not available. Indeed, the best available information for 'GA free' malt is the Australian malting variety Flinders (Paynter 2023).

By repute other varieties that require 'no or low' GA include the Australian varieties Baudin, Bass, RGT Planet, Commander together with Bottler, Buff, and LG Alestar (Blakely Painter, personal communication). Other varieties include Fairview (Malteurop, NZ), Westminster (UK), and the Canadian varieties, AC Metcalfe and CDC Copeland, along with more recent releases CDC Fraser and AAC Connect. Theoretically all Canadian malting varieties (at least those for adjunct brewing) are bred not to require exogenous GA for satisfactory malting (Marta Izydorczk, personal communication). It would appear that the understanding and description of 'GA free' malt varieties is regarded as proprietary by maltsters, breeders and national improvement groupings. All would benefit from a more open approach where the gene/s involved were identified and the interaction with season growing conditions were published.

A novel approach would be to investigate the efficacy of molecular hydrogen (H_2) to influence the biosynthetic crosstalk that modifies plant hormone metabolism after germination and during growth (Li et al 2021a, b). The hormones include GA, ABA, ethylene and jasmonic acid. Importantly for malting, H_2 modulates the transcription of genes for GA/ABA biosynthesis and catabolism to balance the levels of GA/ABA. In rice, the H_2 effect was shown to alleviate aluminium induced inhibition of seed germination (Wu et al. 2020). Indeed, over the past decade, a growing body of literature has demonstrated the efficacy of H_2 to modulate hormones and regulatory enzymes (Table 9). To date, the applications of H_2 have been in horticultural settings providing improvement in the tolerance of stress (heavy metals, salinity, drought), shelf life, disease resistance, and increasing grain/fruit yield and quality. Combined, it is likely that H_2 could be a suitable substitute for exogenous GA enabling the promotion of germination and modification.

Hydrogen gas is relatively inexpensive and widely available and is currently seen as a 'super green' option to combat 'climate change.' Provision of an easily adopted 'malting package' for maltsters would achieve efficiencies in malting and overcome the 'no GA use' hurdle of some brewers. The application of H_2 is relatively simple, being delivered as hydrogen enriched water (HRW) or, with extended residence time in water, nanobubble hydrogen (NBH).

Table 9.

Application of hydrogen to modulate plant and fungal growth, tolerance to stress and post-harvest quality.
HRW – hydrogen rich water, NBH – nanobubble hydrogen delivery.

Species	Application	Delivery	Citation
Alfalfa	Paraquat - tolerance	HRW	Jin et al (2013)
Alfalfa	Heavy metal - tolerance	HRW	Cui et al (2013)
Alfalfa	ABA & drought tolerance	HRW	Jin et al (2016)
Arabidopsis thaliana	Nitrate uptake, seed size	HRW	Cheng et al (2023)
Arabidopsis thaliana	Salinity - tolerance	HRW	Xie et al (2012)
Arabidopsis thaliana	Drought Stress tolerance	HRW	Xie et al (2012, 2014)
Brassica campestris	Cadmium tolerance	HRW	Wu et al (2015)
Cucumber	Drought stress tolerance	HRW	Chen et al (2017)
Ganoderma lucidum	Regulate growth & secondary metabolism of fungi	HRW	Ren et al (2017)
Hypsizygus marmoreus	Alleviate toxicities for mycelial growth	HRW	Zhang et al (2017)
Kiwi fruit	Delay post-harvest ripening & senescence	HRW	Hu et al (2014)
Kiwi fruit	Prolong shelf life	HRW	Hu et al (2018)
Lisianthus flowers	Cut flower senescence delay	HRW	Su et al (2019)
Rose flowers	Improve cut flower vase life & quality	HRW	Wang et al (2020)
Tomato	Disease resistance	HRW	Chen et al (2017)
Tomato	Induced lateral root formation	HRW	Cao et al (2017)
Carnation	Cut flower senescence delay	NBH	Li et al (2021b)
Rice	Grain quality & quantity	NBH	Cheng et al (2021)

The equipment for NBH is off the shelf and relatively inexpensive from China including: (i) H_2 generator (SHC-300), Saikesaisi Hydrogen Energy Co (ii) Portable dissolved hydrogen meter (CT-8023), Shenzhen Kedida Electronics and (iii) NBH (HIM-22), Guangdong Cawolo Health Technology. HRW is phytologically active at concentrations of about 0.5 mM (1 mg/L), which is far lower than the flammability range of hydrogen (4-75%, v/v in air). Of course, monitoring of the atmosphere in steep rooms would be required, with ventilation to ensure the level of H_2 remains < 4%.

Given that malting has several water application phases during steeping and germination, HRW elicitation of GA (and other phytohormones) during malting would be of practical value. If applied during steeping, H_2 would provide GA by elicitation (regulating the activity of GA synthesis) rather than by direct GA addition. The half-life of dissolved H_2 in HRW is approximately one hour (NBH is longer), so there would no residues in malt although maltsters would need to adjust H_2 elicitation to optimal levels. Supplementary applications of HRW/NBH could easily be provided during germination via hydration sprays if required. The practical parameters of optimal timing of H_2 during steeping (germination) and dose rate with respect to malt quality would be established by micro malting and pilot malting trials.

Until recently there were no published reports on the application of molecular hydrogen (HRW or NBH) in malting. Zhu et al (2024) reported the effect of hydrogen-rich water on antioxidant activity during the malting of barley. The technology appears to offer promise in promoting germination and modification via the endogenous stimulation of GA induced enzymes (α-amylase, β-glucanase etc). This would extend the use of hydrogen based agriculture to the agro-processing of fermented beverages and contribute to a carbon-neutral society.

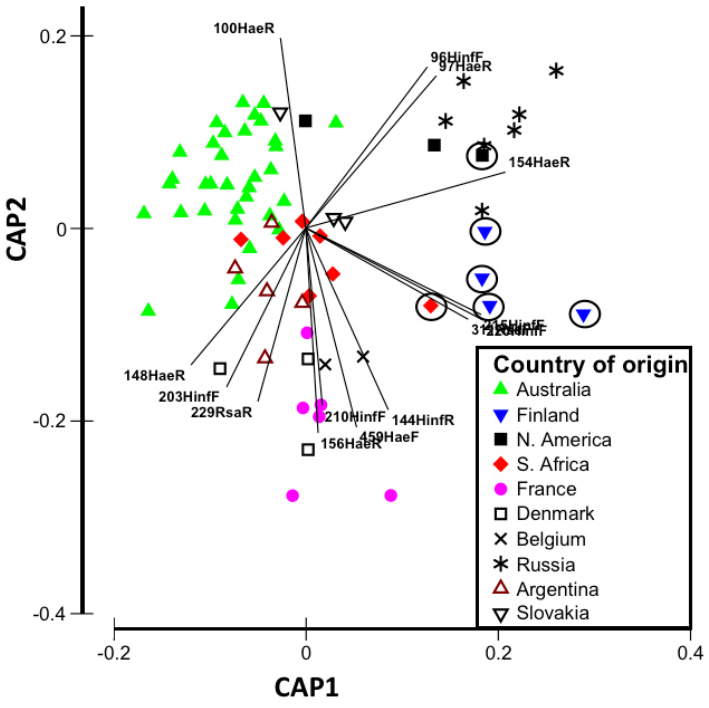
C. Steeping efficiency: microorganisms and starter cultures

The uptake of water by barley during steeping initiates germination but also triggers the the rapid growth of microorganisms present in the barley husk (Petters et al. 1988; Flannigan 2003). The degree to which the grain has been colonised by microorganisms depends on the field conditions under which the barley is grown and the storage of the grain post-harvest. The microbial condition of the barley provides the inoculum which dramatically expands during steeping. It would be expected that microbial community structure and level would differ between grain sourced from the relatively humid and wet climates of Central-Northern Europe and North America compared to Australian barley that is grown under less humid conditions with drier harvest conditions (Birgitte et al. 1996, Backhouse and Burgess 2002; Doohan et al. 2003; Krstanović et al. 2005). Flannigan (2003) suggests that the microbiota of different barleys is similar to each other and to other cereals, being dominated by a relatively small number of species. The microbial species and genera have been reported (Ackermann 1998; Noots et al. 1998; Prentice and Sloey 1960; Follstad and Christnensen 1962; Gyllang and Martinson 1976; Petters et al. 1988; Rabie and Lübben 1993; Turkington et al. 2002; Medina et al. 2006). However, these investigations employed plate culture techniques that underestimate the diversity of microbial populations as microorganisms are unculturable, quiescent or requiring specific conditions (auxotrophy, anoxia). Beyond the understanding of impacts of *Fusarium* head scab infection (Schwarz and Han 2003; Garbe et al. 2009; Geißinger et al. 2022), the diversity of microbiota on barley and malt are the malting manifestation of 'the undiscovered country' of Shakespeare's Hamlet.

Modern microbial genetic protocols such as terminal restriction fragment length polymorphism (TRFLP), DNA fingerprinting and clone library analyses of ribosomal RNA genes (e.g., pyrosequencing) to better assess the diversity of malt microflora. Kaur (2015) reported the diversity of culturable and culture independent microorganisms of malt from different regions. Figure 7 shows the canonical analysis of principal coordinates (CAP) of malt microorganisms in both the Southern and Northern hemispheres. This analysis delineates different groupings between the malt samples. The Australian malt grouping has some association with the other Southern hemisphere growing areas of South Africa and Argentina on the left side of the plot, although those samples are generally lower with respect to the vertical dimension compared to Australia. The circled samples from Finland (four samples), South Africa (one sample) and North America (one sample) were deliberately inoculated with Fusarium and group towards the right side. The French, Danish and Belgian samples locate vertically in the centre but on the bottom compared to the Slovakian and Russian samples that group into the right and upper quadrant. Overall, Figure 7 suggests that differences in malting practices, location and climatic conditions influence the diversity of malt microbiota which may impact on malt quality and the efficiency of malting.

Figure 7.

Canonical analysis of principal coordinates (CAP) of fungal TRFLP data from malt samples based on the Bray Curtis similarity matrix grouped by geographical location. Legends with circles around them represent DON and OTA inoculated Finnish malts, a standard gushing malt sample from South Africa, and a fusarium head blight infected North American malt sample. Vector overlays indicate Pearson's correlations between the ordination axes and individual taxa (only taxa with correlations >0.55 are shown). Figure from Kaur et al (2015) with permission.



Interestingly, the question of microorganisms with respect to barley and malt quality is not always 'black and white' (Laitila et al. 2007), which led Laitila (2008) to provocatively conclude that microorganisms were potentially 'more good than bad'. The positive contribution of microorganisms to malting and brewing include plant growth regulators that enhance germination (GA), vitamins, antioxidants and enzymes (proteases, amylases, β-glucanases, xylanases). The potential negative impacts include inhibition of barley germination (competition for oxygen) and products that impact wort quality including organic acids (pH), exopolysaccharides (wort separation, beer filtration), factors causing premature yeast flocculation (PYF), gushing factors that cause beer over-foaming, allergens and toxic metabolites (mycotoxins).

The isolation of β-glucan solubilase is an interesting case in point in which Bamforth and Martin (1981) originally identified a relatively thermostable enzyme which could survive mashing to increase the level of β-glucan in the wort. Subsequently, Yin et al (1989) provided robust evidence that β-glucan solubilase activity originated from cellulases that were contributed by fungi enabling Fincher (1989) to conclude that the level of barley cellulase in germinating barley was low and was contributed by the grain microflora during the wet phases of malting.

Gushing is a microbiologically initiated malt quality defect that has dominated maltster and brewer attention. It is defined as the spontaneous over-foaming of carbonated beverages (Gardner 1973; Schwarz and Han 2003; Garbe et al. 2009; Geißinger et al. 2022; Rath 2009). A result of infection of barley by *Fusarium* species (*F. graminearum, F. pseudograminearum* and *F. culmorum*), it manifests as '*Fusarium* head blight/head scab,' which infects the barley at anthesis (Backhouse and Burgess 2002; Schwarz and Han 2003). *Fusarium* can also produce undesirable trichothecene mycotoxins (such as deoxynivalenol or DON) in addition to gushing factors such as hydrophobins. In terms of mycotoxins, brewers require routine screening of malt for ochratoxin A and DON to ensure malt safety (Kaur et al. 2015). It is also clear that malting and its associated microbial growth, exacerbates the levels of mycotoxins and gushing factor/s in the malt (Schwarz and Han 2003; Geißinger et al. 2022).

Gushing can also be caused by the presence of calcium oxalate in beer or, more concerningly, through barley/malt fungal hydrophobins together with non-specific LTPs and protein Z4 (Laitila et al. 2007; Deckers et al. 2010; Christian et al. 2011; Shokribousjein et al. 2011). In Europe, gushing can be problem, but depends on the weather in the growing season. A European testing facility using the Carlsberg 'mineral water' test (Garbe et al. 2009; Rath 2009), conceded that gushing effects about 15% of malt samples with bad years (wet grain maturation and harvest) being considerably higher.

The primary method for maltsters seeking to avoid *Fusarium* problems (mycotoxins and gushing) is to select barley that is not discoloured, weather damaged or affected by head scab (Schwarz and Han 2003). However, even slow levels of *Fusarium* can result in problems due to microbial growth during malting (steeping and germination). One approach to minimise the consequences of *Fusarium* on malt has been to use microbial starter cultures to outcompete *Fusarium* (and other microorganisms) during malting (Lowe and Arendt 2004). Typically, *Lactobacillus plantarum* strains (also *Rhizopus oryzae* and *Geotrichum candidum*) have been used which are typically added during steeping (Haikara and Laitila 1995; Laitila et al. 1999, 2002; Schehl et al. 2007). In pilot malting trials, Haikara and Laitila (1995) observed that the use of lactic acid bacteria (LAB) and *Pediococcus pentosaceus* reduced the percentage of *Fusarium* infected kernels in finished malt by 18% and 68%, respectively. However, the levels of kernel contamination were between 90-100% at steeping, regardless of the treatment, which poses the question, what were the residual levels of mycotoxins and gushing factors in the malt? Laitila et al (2002) observed that two LAB cultures could inhibit *Fusarium* species by 40-50% despite relatively small decreases in kernel contamination (1990-1996, 43 trials) compared to the control at the end of steeping (29%) and finished malt (25%). Although the impact of LABs which persist through malting and mashing process to play a positive role in brewing (Vaughan et al. 2005), wort boiling removes viable lactic acid and other bacteria.

Other benefits of starter cultures are reduced malting losses (rootlet inhibition), improvements in malt quality and lautering/wort filtration (Haikara

et al. 1993; Lowe and Arendt 2004). In particular, Schehl et al (2007) observed that malting losses in pilot trails with LAB starter culture achieved a 50% reduction in malting losses. The impact of microorganisms on lautering/wort filtration appears to be associated with the formation of biofilms with a exopolymeric matrix (Raulio et al. 2009). Improvements to lautering/wort filtration by using LAB starter cultures (Haikara and Laitila 1995; Laitila et al. 1999, 2002; Vaughan et al. 2005; Schehl et al. 2007) indicated that the biofilm exopolymeric compounds were effectively suppressed. Maltsters and brewers should be careful when using lactic acid bacteria starter cultures as consideration should be given to the acidification of the malt and resultant wort stream.

Premature yeast flocculation (PYF) represents an intermittent problem for a cohort of major brewers associated with susceptible yeast strains (van Nierop et al. 2006; Lake and Speers 2008; Evans and Kaur 2009). It is possible that more brewers suffer inefficiencies due to PYF that are not attributable due to the lack of a sensitive and cost effective PYF test (Evans and Kaur 2009). The consensus is that the PYF problem is caused, at least in part, by fungi that produce a xylanase to liberate arabinoxylans that prematurely flocculate the yeast before the end of fermentation (Herrera and Axcell 1991 a,b; van Nierop et al. 2004; Koizumi et al. 2008, 2009; Shang et al. 2014, 2020; Xie et al. 2022). An alternative hypothesis for PYF is that causal fungi produce antimicrobial peptide factors that negatively affect yeast metabolism (Okada et al. 1970 a,b; van Nierop et al. 2006; Lake and Speers 2008; Evans and Kaur 2009).

Malting conditions have also been implicated in producing PYF positive malt. Here, the focus has been on steeping, with either too high a pressure on the germinating barley (Yoshida et al. 1979) and/or the use of flat bottom style steeps (Axcell et al. 1986). Anecdotally, PYF malt can be produced from any barley by applying the appropriate steeping conditions (anoxia) although this is tempered by the view that some barleys were easier to make PYF positive malts than others. Presumably, in this case, barley has higher levels of the 'PYF inoculum' due to prevailing field conditions at harvest including temperature, humidity and rain (Lake and Speers 2008).

D. Steeping efficiency: barley steeping treatments and water recycling

An array of chemical and physical treatments have been proposed to reduce barley microflora and to sanitise malt (Vaughan et al. 2005). The treatments include hydrogen peroxide (H_2O_2) (Bishop 1944; Green and Sanger 1956; Rood et al. 2018; Ma et al. 2020), antibiotics (van Campenhout et al. 1998; Laitila et al. 2007; Raulio et al. 2009), electrolysed water (Rood et al. 2018), peracetic acid (Green and Sanger 1956; Rood et al. 2018), UV light (Schildbach 2005), ozone (O_3) (Ma et al. 2020), brief treatment with boiling water (Briggs 2004) sonic (vibration) cleaning (Muller et al. 2015), and chitooligosaccharide (Lan et al. 2016). The generic objective is to reduce *Fusarium* (gushing), PYF or to improve malting efficiency/quality. These treatments by reducing the microbial load may also enable the reuse of steep water. The use of oxidants - H_2O_2 and peracetic acid - in (initial) steep water calls for caution as ROS may exacerbate secondary dormancy germination. Although some of these treatments are benign, others require care as the use of chemical agents necessitates disposal in waste water. Sommer (1977) outlines some of the parameters in play for wastewater disposal. Most jurisdictions have restrictions on the discharge of toxic chemicals in wastewater.

For malt houses where the cost of water and its subsequent disposal is costly, the reuse of steep water is a desirable efficiency and cost objective (Schildbach 2005). This may be direct reuse in steeping or for spraying during germination. However, this requires the improvement of waste steep water quality to maintain the efficiency and malt quality of subsequent malt batches which can decline (Pollock 1959; Griffiths and MacWilliam 1967; Belcredi et al. 2022). Concerns include the fouling of steep water by dirt, microorganisms and detritus from the barley grain. Accordingly, the reuse of steep water results in the inoculation of the next batch of barley with elevated microbial loading leading to reduced malting efficiency and malt quality (O'Sullivan et al. 1999; Schildbach 2005; Belcredi et al. 2022). This will also result in aerobic microorganisms competing for oxygen with the germinating barley. Further, microorganisms produce enzymes and metabolites including bacteriocins, anti-fungal compounds which can

modify pH which can impact malting efficiency and malt quality (Cook and Pollock 1952; Griffiths and MacWilliam 1967; Sommer 1977; Vaughan et al. 2005).

In practice, microbial load, dirt/detritus and enzymes/metabolites need to be controlled in the reuse of steep water to maintain malting efficiency and malt quality. The biochemical oxygen demand (BOD) of used steep liquors has financial implications in the UK for effluent discharge. The BOD of the first step effluent is around 3000 mg/L falling to 2100 mg/L for the second and <1500 mg/L for the third. The first step is to reduce the microbial load by using a combination anti-microbial agents such as O_3 (100 mg/l) and H_2O_2 (200 mg/L) which was reported to be effective by Schildbach (2005). Advances in membrane filtration technology such as cross-flow filtration (Guiga et al. 2008) and reverse osmosis (RO) combined with a membrane bioreactor (MBR) (De Wever et al. 2006) result in recycled water of sufficient quality to support efficient malting and produce satisfactory malt. Guiga et al (2008) made positive observations on commercial trials (30t drum batch) with steep water recycling using the optimal combination of MBR and RO to sanitise the water (Swan 2020). These treatments were sufficient to remove 'the germination inhibitor' such that recycled water could be reused for steeping to yield malt equivalent to conventionally produced malt. However, the water recycling process was only economically feasible when the cost of water and its disposal was relatively high (Swan 2020).

The first commercial system for recycling of steep water was installed in 2018 in Issoudun, France (Figure 8). The Optisteep® system (Dekkers et al 2020) utilises two distinct and continuous steep water phases. The first column contains a selective ceramic carrier that operates like activated carbon, with selective adsorption of non-charged polymeric organic components (polyphenols) that can inhibit barley germination. The second column includes a ceramic catalyst incorporating metal ions (Cu, Fe, Co, Pd) which uses hydroden peroxide to produce hydroxy radicles (OH* and O_2-) and oxygen to produce ionised oxygen (O_2+) and hydroxy radicles that reduce the level of viable microorganisms in the steep water and in higher O_2 levels to stimulate barley germination and growth. In combination, the The Water IQ patent claims that the Optisteep® system saves water (40+%), with reduced water disposal, reduced microbial load and increased O_2 availability. This increases the rate of grain hydration, resulting in lower grain moisture for germination and saves time for steeping by using one continuous wet steep (<20 h) to reduce malting losses and improve malt quality. In 2022, the world's largest malting group, Boortmalt NV installed the Optisteep® system at five locations world-wide (Water IQ, 2023).

E. Steeping efficiency: aeration and CO_2 extraction

Once the grain has germinated it requires oxygen to continue its metabolic and synthetic development (Wilhelmson et al. 2006, 2008). In competition with the germinated barley, microorganisms use O_2 (Doran and Briggs 1993; van Campenhout et al. 1999). As such, differences in microbial load and composition due to field growth and humidity at harvest would be expected to detract from optimal barley germination and growth. Steep aeration is critical during the wet immersion of steeping but care is required to ensure sufficient air flow during the dry rest so that CO_2 does not build up (Haley and Stokes 1987). During these dry phases the steep is ventilated with air to enable CO_2 extraction at rates in the order of 0.71m^3/t/s through the grain-bed. Recently O'Lone et al (2023), applied proteomics to assess the impact of low steep oxygen levels on protein expression in two varieties of barley with differing oxygen sensitivity. Such approaches may lead to the selection of malting varieties with low steep O_2 sensitivity. On the other hand, the maltster needs to ensure that aeration is not excessive as this results in excessive malting losses (Kelly and Briggs 1992).

A constraint with steep aeration is that oxygen is not overly soluble in water, so steep designers need to ensure that aeration nozzles are fine (maximum orifice 0.16 mm) or sintered stones are used, and that the minimum jet density is one jet per 0.3 m^2 (Haley and Stokes 1987). Practically, during the wet phase of steeping, low volumes of air at high pressure are required to give a typical a flow rate of 0.005 m^3/t/s. Of the two modern steep designs, cylindroconical and flat bottomed steeps, the flat bottomed is more efficient for aeration (Aalbers et

Figure 8.

A Water IQ OptiSteep® system installed with a malthouse steep tank, showing dual column system where the first column contains ceramic carrier material for the absorption of germination negative components and the column incorporating the H_2O_2/O_2 dosing system and control equipment in the background. Supplied by Kirsten Dekkers, Water IQ, Netherlands.

al. 1983). However, flat bottomed steeps use 20-30% more water, and are more costly to construct and maintain. Further, the space below the false bottom floor is difficult to clean resulting in the potential cross contamination between batches. In addition, PYF positive malt has been linked to insufficient steep aeration, with the use of flat bottom steeps (Axcell et al. 1986, 2000) anecdotally considered to be a risk. This results from anoxic pockets in the steep through poorly maintained aeration nozzles. Cross contamination due to ineffective cleaning may also play a role. Interestingly, steep anoxia was seen as a way to reduce malting losses (Ponton and Briggs 1969). The role of sufficient aeration to avoid PYF has been adopted as observed by the vigorous aeration of the steep in Figure 9.

The trend towards effective aeration of steeps can be observed from the level of malt limit dextrinase (LD) in the finished malt (Evans and Fox 2017; Yousif and Evans 2020; Evans et al. 2022). Higher levels of steep aeration, presumably to avoid PYF, was suggested to explain the almost double levels of LD observed in malt house WA-A (double steep), PMA (Pilot Malting Australia, rousing for five minutes per hour during wet steep) and more recent malts (Figure 10). Interestingly, other GA influenced enzymes such as α-amylase and Kolbach index (KI) were unaffected (Evans et al. 2022). Further, the high level of LD in all 94 malts produced in Australia and China, where the malt quality from a range of Australian, Canadian and Chinese varieties was described as 'good' and of comparable quality (Evans et al. 2022).

Combined, these insights on the importance of aeration for optimal steeping indicate that maltsters should consider real time monitoring of dissolved oxygen (DO_2) in steep water. This is necessary due to differences between barley pieces in microbial loading, the requirements of the barley variety and the conditions under which it was grown. However, the current technology for measuring DO_2 in steep water are not satisfactory to continuously and reliably measure DO_2. However, this such a system is probably not as useful as the Optisteep system which produces well oxygenated water with the recirculation of steep water (Dekkers et al. 2020).

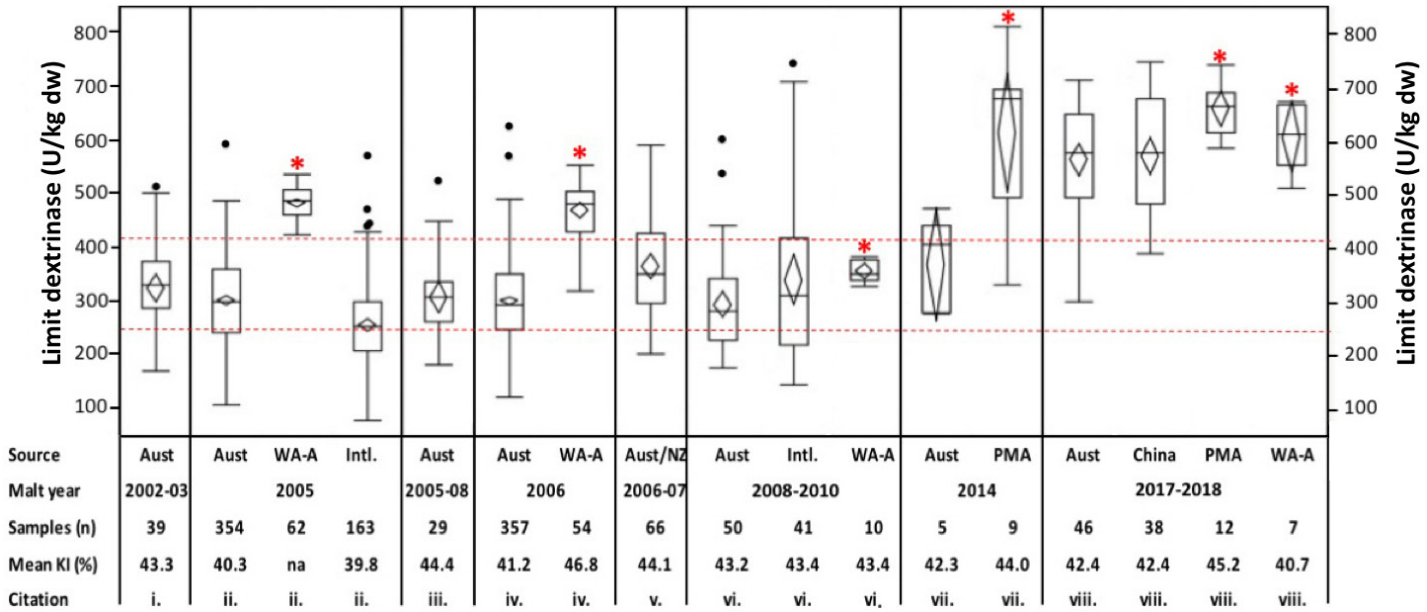
Figure 9.

Cylindroconical steep tank with very vigorous aeration. Photo supplied by Evan Evans.

Figure 10.

Box-plot distribution of the levels of limit dextrinase in commercial malt samples over almost two decades. Horizontal dashed lines indicate range where most data means were observed. Data from Evans et al (2022).

Malt Sources: Aust = Australia, WA-A = Western Australian malthouse with consistently high malt limit dextrinase (Evans et al 2008), Intl. = international malt samples from Europe and North America, PMA = Pilot Malting Australia (100 kg batch), China = Chinese malt from malting primarily Australian and Canadian barley. * Denotes WA-A or PMA malt samples with consistently high limit dextrinase levels.



Citations from: i. Evans et al (2005), ii. Evans et al (2008), iii. Evans et al (2011), iv. Evans et al (2008), v. Evans and Finn (2008, unpublished), vi. Evans et al (2014), vii. Cooper et al (2016), viii. Evans et al (2022).

Improving the efficiency of germination

Optimal steeping conditions should set the course for the efficient production of good quality malt. This is achieved by blowing humid (100%) air through the homogenous grain bed (depth and porosity) to maintain the level of grain moisture at 42-45%. Sprays are applied to provide further control of grain moisture. These sprays are also a delivery mechanism for applying GA (0.1-0.2 mg/kg barley) at chitting (Thomas 2014). Such sprays could also be used to apply HRW to stimulate GA production. Another novel germination additive, the β-glucanase enzyme sprayed during germination, was found to reduce germination time and improve malt quality (Brazil et al. 2019). Periodic turning or raking at eight-hour intervals maintains the porosity of the germination bed, homogeneity and prevents 'matting' of the grain.

To check the progress of malting during germination (and steeping), maltsters have traditionally applied the 'maltsters rub' with their hands and eyes. This test examines how 'gummy' the starchy endosperm is with the cell walls broken down during modification. If rubbing the kernel between the thumb and forefinger produces a smooth paste, the grain is ready for kilning. Obviously, the level of moisture in the barley during germination is a key measure for maltsters. Other novel opportunities to monitor and optimise germination include the measurement of the level of gas effectors in the air efflux from the germination bed. Trace levels of carbon monoxide (CO) (Siegel et al. 1962; Liu et al. 2007; Wang and Liuo 2016) and nitrous oxide (NO) (Floryszak-Wieczorek et al. 2006; Liu et al. 2007; Xie et al. 2014; Cao et al. 2017) impact on physiological responses in germinated grain and plants. Such observations suggest that CO and NO can act as gaseous effectors modulating the levels of GA and plant hormones. Research on monitoring the level of these gases may provide maltsters greater insights into the progress of individual batches to reduce batch to batch variation and produce malt of the desired quality specifications.

It is instructive to consider the development of malt quality and enzymes development (DP enzymes) during malting. There are only a handful of studies that have considered this fundamental aspect of malting. This has been observed from routine analyses and DP enzyme levels in commercial malting (Morrall and Basson 1989; Yousif and Evans 2020), a range of hydrolytic enzymes during micro-malting (Kuntz and Bamforth 2007), and Osborne fraction proteins (Osborne 1924) and amino acids in germinated barley (Folkes and Yemm 1958). Figure 11 shows the changes in malt quality across two Australian malthouses malting two Australian barley varieties using a malting schedule (one day steep, about four days germination, one day kilning) (Yousif and Evans 2020). For the most part, malt quality development begins towards the end of steeping with most occurring during the germination phase.

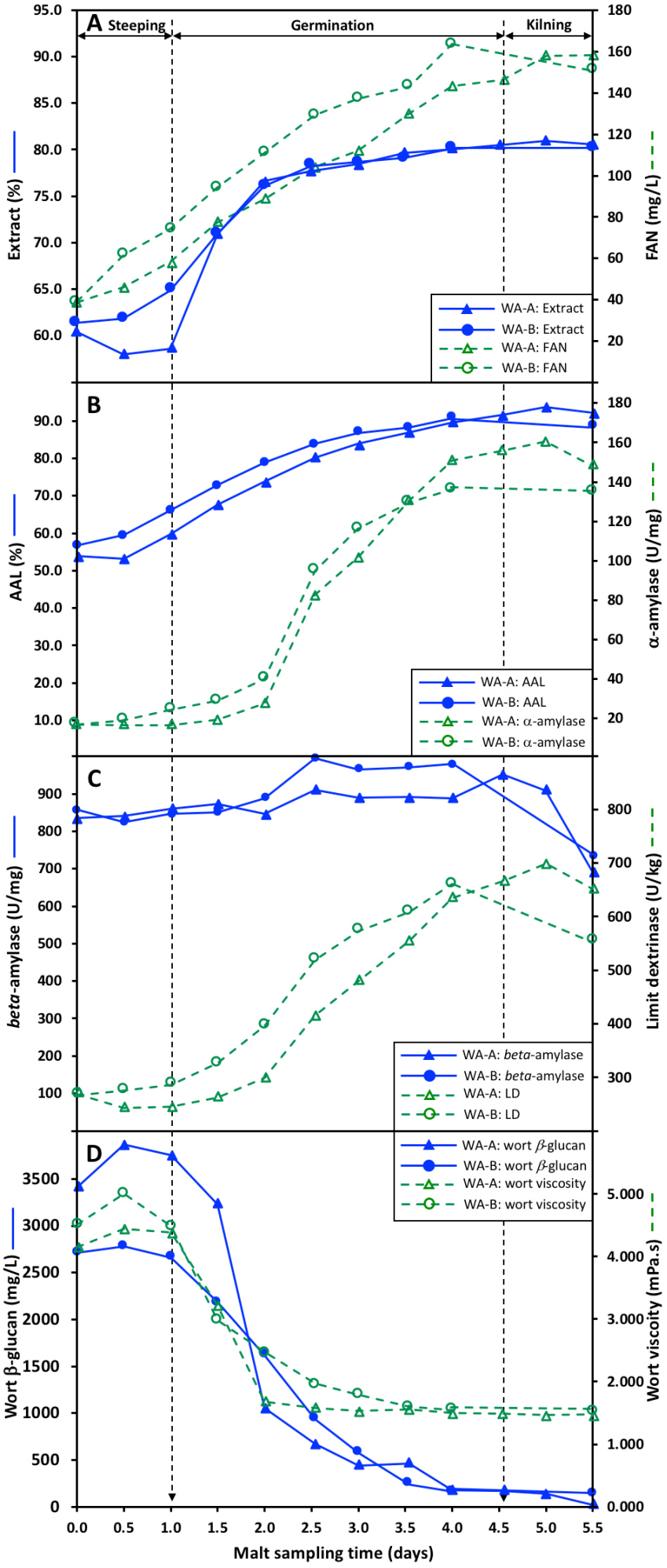
1. Extract 1 - 2.5 days (Figure 11A),
2. AAL 0.5 - 4 days (Figure 11B),
3. LD, α-amylase, 1.5 - 4.5 days (Figure 11B, C),
4. slight increase (release) in *beta*-amylase then kilning decrease (Figure 11C),
5. FAN 0.5 - 4 days (Figure 11C),
6. Wort β-glucan, viscosity 0.5 - 2 days (Figure 11D).

In general, the development of malt quality to kilned malt (Figure 11) is approximately the same level, despite the path of malt development path being different between the two malt houses (e.g., extract or FAN, Figure 11A). The exception is for limit dextrinase (LD) where malthouse WA-A has a higher level than WA-B. The higher level of LD in WA-A has been observed previously (Figure 10) and was attributed to a double steep configuration and a more gentle kilning with a double kiln (Yousif and Evans 2020). Combined these observations provide an understanding of the impact of changes in the malting process to improve efficiency.

Surprisingly, Griggs (2018) observed that malt produced by floor malting (c1870), a Saladin maltings (c1950s) and modern circular maltings (1991) had very similar analytical qualities for two 2-row Winter barley varieties. Broadly similar linkages with malt flavour between floor and pneumatic malting were also observed by Morrissy et al (2024). However, floor malted Maris Otter® when compared to a modern pneumatic maltings, showed clear differences in volatile compositions (Griggs 2018).

Figure 11.

Malt quality and enzyme development during commercial malting in two Australian malthouses (WA-A and WA-B). The average in each malthouse (1-3 batches, Table 10) for two varieties, Buloke and Gairdner: A. Extract and FAN; B. AAL and α-amylase; C. *beta*-amylase and limit dextrinase; D. Wort β-glucan and viscosity. From Yousif and Evans (2020).



These include:

- Lower 1-pyrroline, hexanol, (6Z)-6-nonenal, isoamyl alcohol, 9,12,15-octadecatrienal, pentadecanal;

- Higher alkane, y-n-amylbutyrolactone, α-ethylidene-benzeneacetaldehyde, 1-(1H-pyrrol-2-yl)-ethanone, heptanoic acid, hexanal, hexanoic acid, 2,4-decadienal, furfural, 2,4 heptadienal and 3-hydroxy 2-butanone, myristic acid (ethyl ester), nonanoic acid, hexadecenoic acid (ethyl ester).

It has long been known that the DMS level is a function of malting conditions (Bamforth 2014), where conditions that favour higher protease activity also increase DMS (Kavanagh et al. 1976). Indeed, the level of the DMS precursor in floor malted barley was considerably less (10.8 ± 2.8 µg/g) than pneumatically malted barley (41.0 ± 10.3 µg/g) (Kishnani 2020; Kishnani et al. 2022). Such outcomes are related to the reduced and less efficient air flow through germination beds in floor maltings.

Opportunities for efficiency in kilning

The most energy intensive and costly stage of the malting process is kilning using 80-90% of energy in the malting process (Figures 3, 4 and Tables 4, 6). As such, kilning is the primary target for increasing energy efficiency and sustainability (Davies 2010, 2020; Stewart 2010). Maltsters are now more efficient in their use of kilning energy (Figure 4) which are primarily accrued from the installation of heat exchangers (heat recycling), modifications of kiln airflow and optimisation of kiln heating programs (Yin 2021). Currently the most efficient solution in terms of the energy cost, capital installation and maintenance is indirect heating by gas. Direct gas kiln firing was recognised in the mid 1980's to produce an increase in nitrous oxides (NO_x) which react with dimethylamine in the malt to produce N-nitrosodimethylamine (NDMA), recognised as a carcinogen (Wainwright 1986 a,b; Yin 2021). Currently, alternatives to the use of gas for kilning are being sought due to CO_2 formation from using gas.

The intensity and dynamics of heat during the kilning program results in a significant reduction in the activity of key DP enzymes (Table 10). For the more thermostable α-amylase enzyme, activity is decreased on average by 3.8 -12.7% across two commercial malthouses and malting varieties. Interestingly, *beta*-amylase and LD have similar thermostability during mashing (Evans and Fox 2017) but during kilning between 25.6-36.1% of pre-kiln *beta*-amylase activity is lost compared to 8.6-17.9% of LD activity (Yousif and Evans 2020). These authors suggest that binding of the 14kDa LD inhibitor (~80% of activity) (MacGregor et al. 1994; Evans et al. 2014) provides thermal protection during the kilning process. During mashing it was shown that an inhibitor was released from LD at mash temperatures between 55-60°C (Evans and Fox 2017). It would be expected that the activity of other relatively thermolabile malt enzymes such as endo-proteases, β-glucanase and xylanase would be significantly reduced, however most of their enzymatic action occurs during the malting process (Evans 2021). Conversely, kilning conditions inactivate malt lipoxygenase which reduces beer staling potential (Hirota et al. 2006) and improves foam stability (Evans and Bamforth 2009). It follows that an assessment of malt quality is required when modifying kilning conditions.

Table 10.

Reduction in DP enzyme activity through kilning of two barley varieties (Buloke and Gairdner) commercially malted in two Australian malthouses (WA-A and WA-B). Data from Yousif and Evans (2020).

Malthouse/ Variety	Average DP enzyme activity reduction due to kilning		
	α-amylase (%)	*beta*-amylase (%)	Limit dextrinase (%)
WA-A			
Buloke (n = 3)	6.5	29.5	8.6
Gairdner (n = 1)	12.7	36.1	11.1
WA-B			
Buloke (n = 3)	4.2	25.6	17.9
Gairdner (n = 3)	3.8	31.5	14.1

In searching for a more 'environmentally benign' source of energy, the use of electricity in kilning is appealing despite its cost and inefficiency for heating. In the UK, the Government is considering banning the installation of domestic gas boilers from 2025 with implication for gas fired installations in maltings. Hauner et al (2019, 2020) provides an overview to the development of 'renewable' energy sources such as solar and wind and their implementation application in kilning and the malting process. The pinnacle of this energy pursuit is the 'emission-free' malting plant at Eemshaven in the Netherlands (Biogradlija 2024). Not only is the electricity for all malting functions (turning, transfer, fans, environmental cooling/heating) provided by renewable power but also and, importantly, gas is replaced for kiln heating.

Hauner et al (2020) reported 14 installations of solar heat into maltings and breweries between 1979/1980 and 2019. Perhaps such an approach can be applied to drying germinated grain. However, Hauner et al (2019) contends that solar (and wind) energy can only 'assist' with kilning and malting as provision is intermittent with the provision of mass electrical energy storage is still awaiting development. Other innovations include drying barley with infrared radiation at 40°C (Konopka et al. 2008) and Ferrari-John et al (2017) applied electromagnetic heating for the industrial kilning of malt. Further, Dugulin et al (2021) considered the use of microwave drying (Jones et al. 2002), supercritical CO_2 drying (Smigic et al. 2019) or freeze drying (Brudzynski and Roginski 1969; Ratti 2001). It is noteworthy that kilning and malting are biological processes that require energy to be available 24/7. Accordingly, the energy gap must come from conventional generation of electricity, such as coal, other fossil fuel or biomass generation. While nuclear energy is relatively free of CO_2 emissions, it is a relatively expensive compared to gas and comes with undesirable associations for some people.

The kilning of malt requires different intensities of energy application during the malt drying process with many parameters (bed depth, airflow) first summarised by St. Johnston (1954). Some work has been reported on the production malting varieties that can transferred from germination at a lower moisture content (<40%) rather than 42-46% (Morgan et al. 1983 a,b; Stewart 2010).

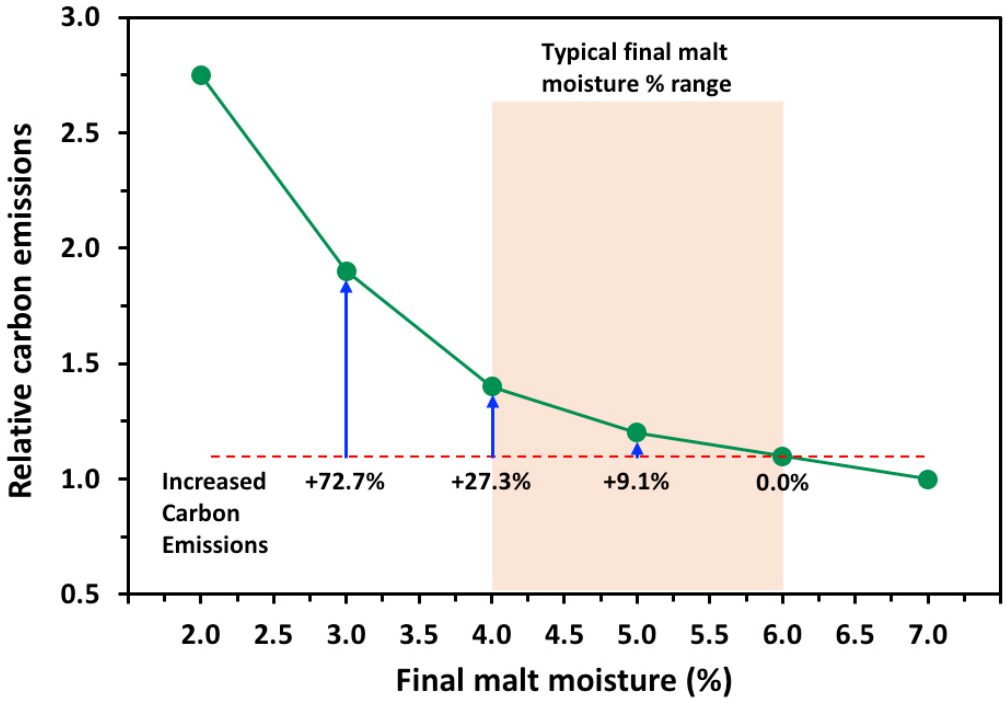
Such a modification would need to be carefully assessed as Figure 11 shows that further improvements in malt quality occur during the early stages of kilning (WA-A, e.g., AAL, FAN, α-amylase, LD). Interestingly, Ditrych et al (2024) recently reported that kilning performed at a lower temperature (65°C), resulted in lower FAN, colour and potential staling products from the Maillard reaction (Strecker aldehydes). This was despite an expectation of higher malt lipoxygenase activity.

Towards the end of the kilning process, the last percentage points of moisture removal from the malt are the most energy intensive. At a malt moisture content of <12%, removal of water requires substantially more energy to remove 'bound' water (Dugulin et al. 2021). Figure 12 shows that approximately 27.3% in relative CO_2 emissions (energy) is needed to reduce moisture content from 6 to 4%, identifying a potential area for energy saving. However, Maillard products are formed by the reaction between amino acids and simple reducing sugars to create colour and flavour (Hodge 1953; Ames 1988). The kinetics of these reactions are favoured by high concentrations of the substrate (low water contents) at relatively high temperatures. It follows that kilning to a reduced level of malt moisture would modify the desirable flavour attributes of malt (Davies 2006). A higher standard malt moisture of 6% would also have potential benefits in terms of husk integrity (with desirable impact on lautering) and greater preservation of thermolabile malt enzymes such as *beta*-amylase and LD (Yousif and Evans 2020). Presumably, the moisture specification of 6% for whisky malt is to protect these important enzymes

In storage, to avoid undesirable microbial growth, the upper limit for malt moisture is <14% (Flannigan 2003; Albini et al. 2018; Martynov et al. 2018). Excess moisture above 6% increases shipping costs, reduces brewhouse yield and results in a decline in malt quality during storage (Schoals and Heinrich 2020; Montana State University 2023). In addition, higher malt moisture impacts on friability with dry roller mills due to changes in the dynamics of malt crushing, although such issues can be remedied by using a wet mill (Evans 2021).

Figure 12.

Relationship between carbon equivalent of energy used in kilning and final moisture content. A final moisture content of 3 and 6% equates to a 72.7% saving. The differential between a final moisture content of 4 to 6% equates to a 27.3% saving. After Davies (2010), reproduced with permission from the Master Brewers Association of the Americas



A novel solution is to remove the kilning process and use 'green malt' which would provide substantial savings in energy and emissions. A comprehensive review has been published by Dugulin et al (2021) and the key insights outlined below. Useful overviews of the impact of malt killing on malt components can also be found in Bathgate (1973) and Karel (1965).

• **Storage:** Green malt has a moisture content of 42-46% which does not result in the stopping of microbial and plant growth. The primary aim of kilning is to ensure malt storage (stability) and transportability. Spraying the green malt with a short burst of boiling water as advocated for barley (Briggs et al. 2004) may reduce microbial growth but not the physiological activity in the grain. This could be combined with storage at 4°C – which is expensive - but would control microbial growth and grain metabolism. Alternatively, freeze drying (Brudzynski and Roginski 1969; Ratti 2001) could be a solution (Yousif and Evans 2020), but again is currently uneconomic. Combined, making green malt storable for transport, malt quality assessment and blending across multiple brewing batches is required for green malt is to be commercially viable.

• **Malt flavour and colour:** Maillard compounds and Strecker intermediates (Hodge 1953; Ames 1988) are formed during the curing stages of malting from a combination of FAN, simple sugars and heat. Although Maillard compounds are desirable (Davies 2006; Omari et al. 2021) they can be undesirable as contributors to beer staling during storage (Drost et al. 1990; Gastl et al. 2006; Vanderhaegen et al. 2006; Baert et al. 2012). Green malt brewing trials reported by Dugulin et al (2020) showed that wort colour was lighter than from conventionally kilned malt. Such issues could be ameliorated by the use of specialty malts (crystal malt, caramalt etc) (Evans 2021). Alternatively, brewers could use concentrated malt flavour extracts (PureMalt, UK) to compensate for deficiencies.

• **Milling:** Roller and hammer 'dry' mills are not compatible with the high moisture content of green malt (Evans 2021). Dugulin et al (2020) found that a wet mill (Meura Hydromill) at a pilot scale can successfully mill green malt. However, some optimisation of milling is required to reduce extract loss and assure filterability.

• **Thermolabile enzymes:** Kilning reduces the levels of DP enzymes by 3.8-36% (Table 10, α-amylase < LD < *beta*-amylase) which would be expected to increase attenuation and produced 'drier' beers (Yousif and Evans 2020). Kilning also reduces the amount of β-glucanase activity by 40% (Sissons et al. 1995; Hamalainen and Reinikainen 2007), although the enzyme acts primarily during the malting process (Yousif and Evans 2020; Evans 2021), although Jin et al (2004) concluded that high levels of the enzyme in malt were 'advantageous.'

• **Lipoxygenase and beer stability:** In green malt there are two lipoxygenases present. LOX 2 is synthesised after grain germination but is thermolabile (above 45°C), while LOX 1 is synthesised during barley maturation and is more thermostable (~45°C) (Hugues et al. 1994; Yang and Schwarz 1995). A combination of rootlets and malt acrospires which remain with green malt contain significant levels of lipoxygenase and substances causing unpleasant aftertaste/astringency (Yang et al. 1993; Tada et al. 2004; Kageyama et al. 2011, 2013). With kilning, LOX 2 in rootlets is inactivated, as is a significant portion of LOX 1. Beer flavour is further improved by removal of acrospires and rootlets after kilning. Lipoxygenase activity is undesirable as it produces staling compounds such as trans-2-nonenal (Bamforth 2000; Vanderhaegen et al. 2006) and lipid hydroperoxides that destabilise beer foam (Evans and Bamforth 2009). A further impact of higher LOX during mashing could be the reduction of protein disulfide linkages, similar to lipoxygenase in bread proving (Casey 1997). Reduced proteins could together and impede lautering via an enhanced gel protein or obertieg layer. Indeed, Dugulin et al (2020) in their green malt brewing trials did observe a poorer lautering performance. To counter the undesirable higher levels of lipoxygenase in green malt, Dugulin et al (2021) suggested that LOX null varieties would be preferable (Takoi et al. 2004, Skadhauge et al. 2010) and higher mashing in temperatures (>62°C) would be less favourable to LOX action. Alternatively, a brief treatment with steam or hot water (Briggs 2004) would denature the exposed lipoxygenase in rootlets and acrospires. This treatment would also have the beneficial effect of reducing the microbial load on the green malt.

• **DMS:** Green malt is rich in the dimethyl sulphide (DMS) precursor S-methyl methionine (SMM) (Dugulin et al. 2021). The thermal precursor to DMS is catalysed by L-methionine S-methyltransferase (MMT) (White and Wainright 1976; Pimenta et al. 1998) which further decomposes into DMS with heat during kilning. The volatility of DMS results in the removal of a significant amount of DMS during kilning. Consequentially, the absence of kilning with green malt results in a greater DMS potential in wort made from green malt. Dugulin et al (2021) suggests that excess DMS could be removed from the wort via enhanced wort stripping during the kettle boil and by using barley from a double LOX 1/2 and MMT null barley variety (Knudsen et al. 2011).

Storage and blending

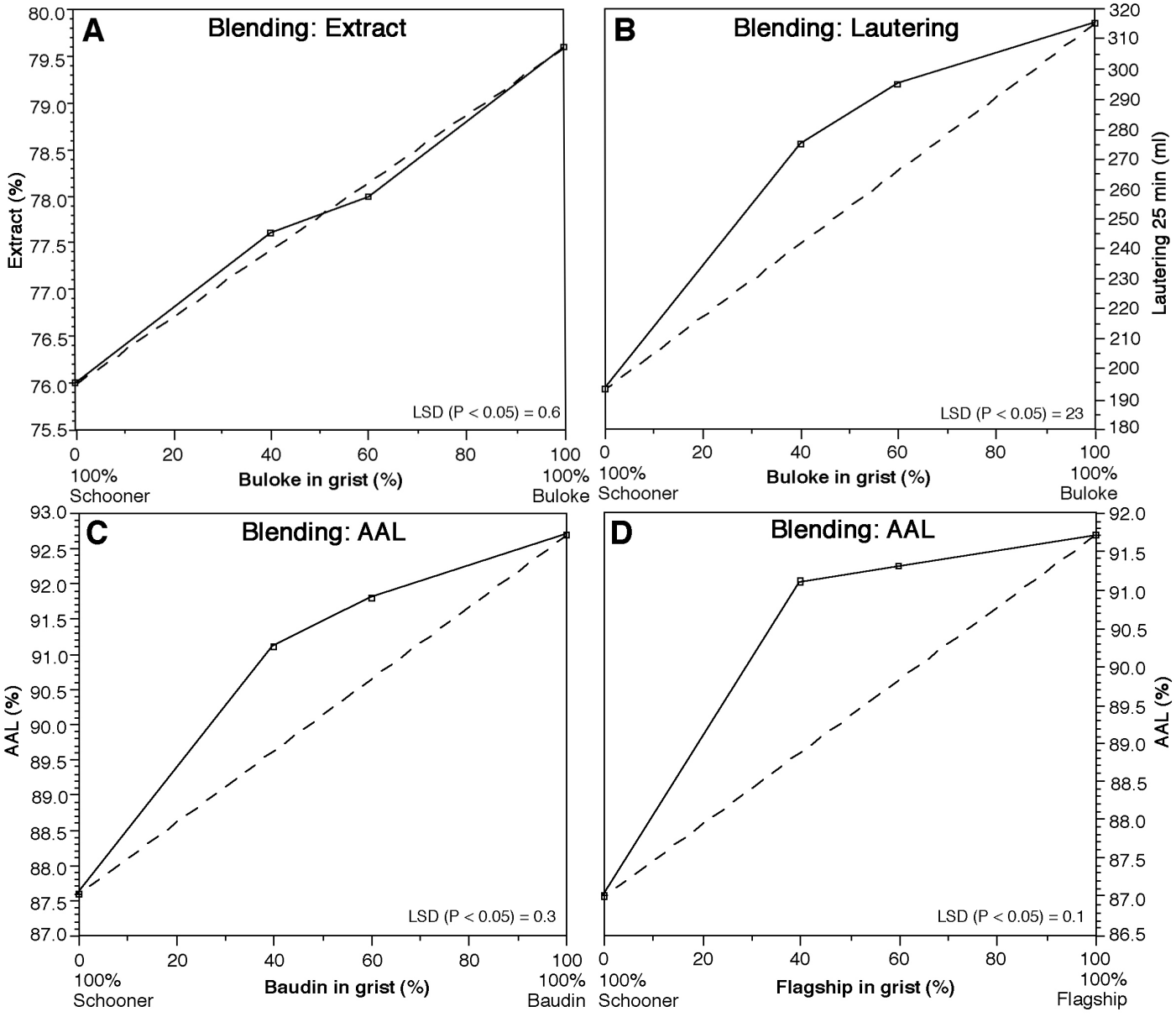
One of the key skills of a maltster is the ability to blend batches of malt to provide malt that matches the malt quality specifications. The assumption is that the variation between malts largely additive (Evans 2012; Figure 13A). However, Figure 13B shows that a small-scale assessment of lautering between a malt with low β-glucanase levels (Schooner) and a malt with high β-glucanase levels (Buloke) results in synergy between the blended malts. This is despite most β-glucanase action appearing to occur during malting process (Yousif and Evans 2020, Evans 2021). Such synergy concurs with the conclusions of Jin et al (2004) that high malt levels were 'advantageous,' despite a modified infusion mash protocol at 65°C being used (Evans 2012). More dramatically, Figures 13C and 13D show that there is substantial synergism between malts with varying levels of DP enzymes with respect to wort attenuation. Figure 13C shows that when Schooner malt with low levels of *beta*-amylase (and thermostability) (Eglinton et al. 1998; Evans 2012) is blended with a Baudin malt, the higher *beta*-amylase activity in this malt supplements the overall malt level to increase attenuation. Similarly, Figure 13D shows that Flagship malt with intermediate *beta*-amylase activity, high *beta*-amylase thermostability and higher α-amylase activity results in a positive improvement in attenuation. Such blending synergisms (or potential antagonisms) for malt

Figure 13.

Impact of mashing blended malts on fermentation. The dashed line represents the expected extract levels if fermentability was additive. A. Baudin into Gairdner, B. Buloke into Schooner, C. Baudin into Schooner, D. Flagship into Schooner. Data from Evans (2012). Reproduced with permission from the American Society of Brewing Chemists.

Quality characteristics of malts used for malt blending experiments

Variety	Fine extract (%EBC)	Protein (% dwt)	KI (%EBC)	DP (°WK)	Sd type *beta*-amylase	*beta*-amylase (U/g dwt)	α-amylase (U/g dwt)	Total limit dextrinase (U/kg dwt)	β-glucanase (U/kg dwt)	Viscosity (mPa.s)
Baudin	81.8	11.8	48.0	453	Sd1	707	177	334	364	1.42
Buloke	81.6	10.7	47.6	383	Sd2H	823	251	450	523	1.50
Flagship	82.7	11.2	46.0	365	Sd2H	537	208	323	293	1.47
Schooner	79.7	11.0	48.3	184	Sd2L	350	165	318	118	1.63



quality characteristics result from mash based enzyme activity (attenuation from starch hydrolysis). Maltsters that are unaware of such 'specific combining abilities' between malts may miss specified targets leading to unwelcome surprises for the brewer.

With respect to malt storage, the practical considerations are straight forward. Short term storage is required to hold malt batches as they are produced to enable analysis of malt quality. Further, storage is required to hold malt batches from different varieties and of varying qualities. Even within varieties, there can be variation in malt quality (Evans et al. 2022) due to different barley origin or terroir resulting in different levels of protein (Evans et al. 2023). The other storage factor is that freshly kilned malt requires to 'rest' for 2-4 weeks to avoid problems with mash separation/lautering (Rennie and Ball 1979). Bamforth et al (2009) found this requirement for malt storage to be related to malt thiol oxidase.

Barley Brewing

A novel alternative is to undertake 'barley brewing' and to produce beer from barley by supplementing the mash with a cocktail of exogenous enzymes. The concept of barley brewing stems from Labatt Breweries in 1966 (Latimer et al. 1966). To date, there are two enzyme cocktails used in barley brewing: Ondea Pro® (Novozyme, Denmark) and Brewers Compass® (DSM), with two enzyme cocktails Promalt® and Deltamalt® used for high adjunct brewing (>50% adjunct + malt) (Table 11). Ondea Pro appears most widely used (Steiner et al. 2012; Evans et al. 2014; Zhuang et al. 2017), and includes a combination of: (i) pullanase/α-amylase; (ii) β-glucanase/xylanase; (iii) endo-proteinase; and (iv) lipase. Barley contributes *beta*-amylase, exo-proteases and the undesirable LOX 1 (staling and reduced foam) (Evans et al. 2014).

Table 11.

Malt enzymes and commercial mashing enzyme cocktails for barley brewing or high adjunct brewing[1].

Enzyme targets Mashing	Malt brewing		Barley Brewing			High adjunct brewing	
	Conventional malt mashing	Mash outcome	Barley enzyme contribution	Ondea Pro® (Novozymes)	Brewers Compass® (DSM)	Promalt® (Kerry)	Deltamalt® (Deltagen)
Starch hydrolysis	• α-amylase • *beta*-amylase • limit dextrinase • α-glucosidase	yeast fermentable sugars (e.g., glucose, maltose, etc	*beta*-amylase (limit dextrinase)	pullanase/ α-amylase	pullanase/ α-amylase	amylase	α-amylase
Cell wall hydrolysis	• β-glucanase • xylanase	low MW. β-glucan low MW. pentosans mash/wort filtration	(β-glucanase)	cellulase (β-glucanase /xylanase)	β-glucanase, arabinoxylanase hemicellulase	glucanase, cellulase	β-glucanase
Protein hydrolysis & release	• endo-proteinase • exo-proteinase	protein release: foam reduced haze protein FAN (amino acids)	Exo-proteinase	endo-proteinase	protease	protease	protease
Lipid release & oxidation	• lipase • LOX 1 (LOX 2)	reduce wort turbidity foam instability (LOX)	LOX 1 (lipase)	lipase			

Table after Kok et al (2019). Enzymes in parentheses signify relatively low enzyme levels

Small-scale trials indicated that extract and attenuation were greatest when a malting variety of barley (with moderate GPC) was used used in barley brewing. The level of grain protein had a significant impact on wort quality parameters. Higher grain protein increased soluble nitrogen, free amino nitrogen and barley *beta*-amylase levels but reduced extract, barley KI, wort β-glucan and colour (Yousif and Evans 2018). Interestingly, the efficiency of barley brewing was promoted using barley with high levels of *beta*-amylase with Sd2H *beta*-amylase thermostability (Evans et al. 2014, Cooper et al. 2016) and higher free (~60%) Sd2 type barley *beta*-amylase (Evans et al. 1997). Although Ondea Pro enables barley to be used for brewing, there are advantages from including of 10-20% malt improve brewing efficiency (extract, lautering, fermentability, FAN and haze) (Cooper et al. 2016).

In common with green malt, there are considerations with barley brewing barley with respect to milling and flavour. Since barley is not kilned, barley wort would lack the complexity and desirable range of Maillard products. This could potentially be ameliorated by the inclusion of specialty malts (crystal malt, caramalt) or concentrated malt flavour extracts (Evans 2021). Another consideration is that harvested barley contains dirt, microorganisms and debris. Therefore, it is advisable that barley is washed before milling with a wet mill (Evans 2021). Alternatively, the use of hulless barley would be of benefit.

Conclusions

Located between the production of agricultural barley and brewing, malting occupies '*the middle parts of fortune*' in the brewing process. Since settled human existance began in neolithic villages some 10,000 years ago, malt of some form has been made. The malting process begins with the selection of sound (germinable) barley, followed by careful storage. Barley is cleaned and grading before being imbibed with water (steeping) typically for one to two days. Once the moisture content reaches 40-46% and before chitting, it is cast into germination boxes. It is allowed to develop at 12-16°C, 100% humidity and a constant flow of air through the bed for three to five days. Once germination is complete, the green malt is transferred to the kiln where the malt is dried at temperatures starting at 50°C (withering) and completed with curing at 80-85°C. After kilning the malt quality is assessed and may be blended with other batches to meet quality specification demands. The engineering configuration and efficiency of modern pneumatic maltings owe much to the innovation of two Belgian-French malting engineers in the late 1800's, Nicholas Galland (pneumatic, drum malting) and Charles Saladin (pneumatic, false floor, turning screw). As such, this review has focussed on the efficiency of pneumatic rather than floor maltings.

Since the time of Saladin and Galland, continual innovation in the malting process has achieved efficiencies in terms of energy, water, labour, capital and malt quality. The current imperative for innovation is for greater energy efficiency in terms of cost and CO_2 emissions. In terms of energy efficiency, 80-90% of energy expenditure in malting is for kilning. However, the production of nitrogen fertilisers to grow high yielding barley requires significant energy (30-50% of kilning). There is limited scope for economy in the level of nitrogen fertilisation, as barley yield is directly and positively linked. In terms of malting water use, most is used during steeping and discharged to waste (at a cost). Overall, the efficiency of the malting process is the time taken to convert barley into malt (energy, water, labour and capital costs) and minimising malting losses. Maltsters regard malting losses of 18-20% (barley weight) as unavoidable.

The elements of the malting process that can be targeted to maintain or improve efficiency are as follows:

• **Barley variety and quality selection:** The malting barley must be sound (>95% germinable), <14% moisture to minimise microbial growth during storage and with minimal weather damage which can indicate microbial contamination such as *Fusarium*, mycotoxins, gushing or premature yeast flocculation. Ideally, the grain will have a modicum of dormancy to prevent post-harvest sprouting but not to inhibit the efficiency of germination. There are two types of dormancy: (i) primary dormancy (genetic/season, ABA/GA balance), and (ii) secondary dormancy (due to protracted storage or excessive temperature). Malting varieties should produce high quality malt

(extract, enzymes, attenuation etc.), with varieties that do not require the application of gibberellic acid in the malting process being desirable in some markets. Malting barley selection relies heavily on grain protein content (GPC) because GPC is positively correlated to DP enzyme levels, foam positive proteins and FAN, but negatively correlated to extract, KI and, possibly, flavour intensity and complexity. Generally, the acceptable level of GPC for malting barley is 9-13%. Hulless barley has been considered with promising results due to the reduced weight of the grain (~11%) and transport volume but work remains to make hulless malt commercially viable. Finally, malting barley is an agricultural product that is subject to the vagaries of terroir and seasonal variation (drought, wet harvest) which can constrain the purchase options of the maltster.

• **Steeping:** Practicing maltsters understand the maxim, that good quality malt requires the right steeping conditions. During the wet, submerged phases of steeping, it is important that sufficient levels of oxygen are available to the grain for respiration. Satisfactory aeration of the steep also avoids the development of the PYF syndrome and results in almost a doubling of limit dextrinase (LD levels. It is during steeping the GA can be applied (1-2 mg/kg barley). GA treatment improves malting efficiency by expediting modification and the accumulation of enzymes (α-amylase, β-glucanase, endo-proteinases, etc). Recently a potential 'green' alternative to GA, hydrogen enriched water (HRW) has been identified. HRW can influence the biosynthetic crosstalk that modifies plant hormone metabolism resulting in the idigenous synthesis of GA and other growth hormones. For reducing steep water, the Optisteep® innovation has shown commercial promise by recycling, sanitising, oxygenating and filtering steep water such that one long steep is required, saving around 40% of water use.

• **Germination:** The germination stage is the longest malting stage (three to five days) but requires comparatively low inputs of energy and water. Many maltsters favour applying GA (0.1-0.2 mg/kg) at the start of germination and after chitting, to avoid damage during transfer to the barley germ. Here, the application of H_2 (HRW) during the germination phase could be explored as could the level of carbon monoxide (CO) and nitrous oxide (NO) in air exhausts to monitor malt development. Both CO and NO are trace gases that have been shown to regulate the level of plant hormones such as GA.

• **Kilning:** Kilning is the highest user of energy during malting (80-90% of total malting energy). Over the past 20-30 years, maltsters have been able to improve kilning efficiency by at least 30% by improved heat exchange and optimised kilning programs. During kilning the moisture content is reduced from 42-46% in the green malt to 4-6% in finished malt. Kilning effectively stops all malt and microbial metabolic activity to produce a product that is storable and transportable. Heating during killing also promotes the accumulation of Maillard products that contribute flavour and colour and minimises the level of lipoxygenase (staling potential, foam inhibition). By way of reducing kilning energy, kilning with green malt moisture levels of <40% is viable as the water is relatively easily removed from green malt. At the other end of the spectrum, increasing malt moisture from 4-6% to ~10% although initially attractive but the bound water requires significant energy to remove. However, limited reports suggest that malt stores poorly > 9% moisture.

Currently, engineering considerations suggest that indirect gas firing is the most energy and capital efficient energy source for kilning. Other small-scale investigations have explored the use of infrared radiation at 40°C, electromagnetic heating, microwave drying, supercritical CO_2 drying and freeze drying. These options require electrical energy that could be provided, at least in part, by 'renewable' energy such as wind and solar.

• **Green malt and barley brewing:** Using green malt for brewing has several advantages including energy savings (kilning), moisture 42-45%, reduced loss of thermolabile malt enzymes (*beta*-amylase, β-glucanase). However, the challenges of brewing with green malt are substantial. The malt cannot be stored or transported, it requires wet malt mills and undesirable lipoxygenases are not inactivated with the rootlets retained adding further lipoxygenase and astringent compounds. As there is no kilning, the characteristic and desirable malt Maillard products are not formed, although these could be added by including specialty malt or addition of

concentrated malt extract. At the opposite end of the scale, there is the 'unromantic' but practical approach to brew beer directly from unmalted barley in conjunction with enzyme cocktails that remove the cost of malting altogether. Like green malt, barley brewing is hampered by the lack of Maillard products, but this can be ameliorated as with green malt. In addition, an inclusion (10-15%) of malt to the grist can improve the efficiency of the process.

• **Storage and blending:** Sufficient malt storage is required to separate batches for analysis, for separation of varieties and by malt qualities. Malt is hydroscopic, so the storage silos should be sealed to minimise moisture ingress. Although blending of malt is routine, maltsters should be aware of potential synergies or antagonisms between malts of varying quality.

Overall, there are numerous opportunities for maltsters to improve efficiency in terms of malt quality, duration, water and energy.

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