Title
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Permalink
https://escholarship.org/uc/item/9w45010t

Journal
Journal of the Institute of Brewing, 126(1)

ISSN
0046-9750

Author
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Publication Date
2020

DOI
10.1002/jib.594

Peer reviewed
The Horace Brown Medal.

Forever in Focus: Researches in Malting and Brewing Sciences

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+ Six presentations were made on the various facets of this work in 2019, in Manchester (March 19), Edinburgh (March 20), Dublin (March 21), Sutton Bonington (March 26), London (March 28) and Vienna (April 16).
Abstract

The paper reviews a career of more than forty years researching topics in malting and brewing science. Some themes attracted particularly close attention, namely the endosperm cell walls of barley, dimethyl sulphide, flavour stability, foam and the impact of beer on health. However the scope has been far broader than that. The underlying imperative was to pursue research that was close to application and always focussed on a specific need in the processes involved in the production of beer.

Key words: β-glucan, cell walls, dimethyl sulphide, flavour, foam, health, oxygen, stability,
Direction in Research

For the greater part of two centuries the study of beer has presented the opportunity for countless fundamental discoveries to have been made in science generally, findings of far more relevance than for their significance in beer alone (1). Indeed while some of the breakthroughs emerged from a fundamental process or quality need in the production of beer (e.g. the elucidation of pure yeast technology, 2), in rather more instances the research involved was of a rather “purer” nature, by which I mean more a case of research for the sheer need to unravel the unknown as opposed to endeavours in pursuit of solving a problem. Examples of this would be the elucidation of the concept of pH (3).

At the time that I was directing the fundamental research program of BRF International in Nutfield, England, I wrote of the sequence of research, from pure (fundamental), through pre-competitive (strategic) to competitive (applied) (4, 5). For my part, irrespective of whether I was employed by a research station [Brewing Research (Foundation) (International; BR(F)(I)), a brewing company (Bass and latterly Sierra Nevada) or academia (the University of California, Davis), a fundamental question I have always asked prior to embarking on a research project (whether at the bench or more theoretical) was “might this having a meaningful application either directly or indirectly in malting or brewing?”. If the answer was “no” then I would never pursue that project. I have spelled out the areas in which I believe that malting and brewing research should be focused (4, 6, 7, 8) and I have highlighted one approach to project selection (5).
I have never felt there to be a shortage of intriguing topic areas that fall within these guidelines. An innate curiosity in diverse areas, then, has meant that I might fairly be accused of dipping into many topics without sufficiently dotting all the I’s and crossing all the t’s in any of them. The good news is that, hopefully, it has left plenty of scope for others (if they are so inclined) to fill in the gaps. I respectfully highlight some of the potential future research projects herein.

Having said that, there have been several themes that have garnered my attention more keenly than others and they will be readily identifiable as this discourse continues.

The cell walls of barley

The efficient degradation of the cell walls of the starchy endosperm of barley is critical if the brewer is not to encounter problems with reduced extract yields, solid-liquid separation challenges and increased risks from turbidity (9, 10, 11). However it can equally be highlighted that the soluble fibre derived from an incomplete digestion of the principle cell wall constituents of mixed-linkage β-glucan and (especially) arabinoxylan (pentosan) does lead to beer frequently being a good source of soluble fibre (12, 13), whilst the almost comprehensive digestion of β-glucan to oligosaccharides generates end products that we showed to be prebiotics (14).

My first foray into the subject of β-glucans was working alongside Hilary Martin in developing an enzyme-based method for quantifying the levels of the primary cell wall component in barley (15, 16).
At first the method was based on converting β-glucan to enzyme-assayable glucose using a cellulose preparation from *Trichoderma viride*. That a cellulose (endo-β-1,4-glucanase) is capable of completely converting mixed linkage β1,3; 1,4-glucan to glucose indicated that there must be β1-3 glucanase activity present and I purified and characterized an exo-acting enzyme from *Trichoderma* (17). We needed to eliminate amylglucosidase, which would otherwise lead to erroneously high values as the contaminant would generate glucose from starch. This removal was effected using heat, however we found that some batches proved more intransigent to this procedure than did others, so we switched the enzyme source to *Penicillium funiculosum* which was much more reliable in this regard (18).

Reading around the topic of cell wall degradation at the time focused my attention on the work of Ian Preece in Edinburgh (19) and Bill Meredith in Winnipeg (20). Preece spoke of cytoclastic and cytolytic reactions, whilst Meredith intriguingly used the proteolytic enzyme papain to solubilize a proportion of gum. Of particular curiosity was a paper by Bendelow in 1973 (21), in which he wrote

*We have evidence that the rate of release of beta-glucan from a protein-carbohydrate matrix in the cell wall is a limiting factor in modification and in the reduction of viscosity during mashing. And in this connection, the use of barley as an adjunct comes to mind. It appears that we must look for, and measure, some proteolytic enzyme that releases bound glucan for attack by the glucanases, and then incorporate high levels of this protease in new barley varieties - or modify the cell-wall structure.*

I took in a short paper by Bob Scott (22) in which he discussed a heat-tolerant enzymic activity in malted barley that brought β-glucan into solution. With Ms Martin’s meticulous technical support, I determined
to identify that enzyme (15). We confirmed that there is freely soluble β-glucan but demonstrated that there most definitely is an activity that enhances the solubilisation of glucan and that a proportion of this enzyme is already present in raw barley, thus indicating that it is not endo-β-glucanase (15). I gave it the name solubilase, which compatriots seemed to either love or hate. More solubilase is developed during germination (23).

We identified the enzyme from raw barley as being a carboxypeptidase acting as an esterase. Denise Baxter had previously tentatively suggested that carboxypeptidase might be involved in the degradation of the cell walls (24).

Joanne Moore pursued the solubilase story further and from her work we drew the conclusion that there are four different solubilase fractions in malt (25). One of these was confirmed as carboxypeptidase, with the others displaying activity as xylanase, ferulic acid esterase (26) and “general” esterase (not carboxypeptidase).

It was only later, in Davis, that my outstanding post-doctoral fellow Makoto Kanauchi and I were able to drill down on this story in depth. (Dr. Kanauchi and I have now collaborated for more than two decades.) Two main approaches were employed. The first was to grow Trichoderma viride on barley cell walls, the rationale being that the organism would synthesise the enzymes in the sequence that it needs them to attack the substrate (27). We found that there was an early release of xylanase, as well as of carboxypeptidase. Furthermore, it was shown that pentosan was released before β-glucan. The second approach was to treat isolated walls with a series of highly purified enzymes (kindly supplied to us by the
Novozymes research team in Davis) and to measure the extent to which \( \beta \)-glucan could be solubilized by them (28). Intriguingly it was shown that xylanase was the most powerful enzyme for solubilizing \( \beta \)-glucan, whereas endo-\( \beta \)-glucanase could not solubilize arabinoxylan. We also found that there was a small contribution from arabinofuranosidase, feruloyl esterase and acetoxylan esterase, but their effect could most clearly be seen using scanning electron microscopy, with a clear cleaning up of the surface of the walls, rather like the de-fuzzing of wool (29).

Based on these data, we proposed a model for the cell wall of barley (30), in which the pentosan is concentrated on the outside of the wall and the \( \beta \)-glucan on the inside. That glucanase could effect some release of glucan indicated that there was not a total shielding of the inner wall by the outer wall. The external presence of the arabinoxylan was consistent with the aforementioned cleaning up of the wall appearance by the esterases, it being known that ferulic acid and acetic acid are linked through ester bonds to the pentosan. Palmer had already suggested that pentosan was concentrated on the periphery of the wall (31).

Further relevant experimentation included that by Kuntz and I (32), showing that xylanase, arabinofuranosidase and carboxypeptidase develop before endo-\( \beta \)-glucanase in germinating barley. Furthermore, Scheffler and I showed, in mashing studies with high barley loadings and commercial enzymes, that xylanase worsened the viscosity situation at low doses, \( \beta \)-glucanase improved it, but that a mixture of xylanase and \( \beta \)-glucanase was the most effective way to deal with adjuncts as gauged by viscosity, wort separation rates and extract yield (33). This is readily rationalised by xylanase making the glucan more available for digestion.
To this day we have no notion of the bond(s) that are broken by carboxypeptidase in the solubilase action! Originally, we surmised that they were ester linkages between carboxyl groups in the protein that is known to be present in the wall and hydroxyl groups in the glucan. Tentatively we indicated that it may have something to do with the protein-rich middle lamella between adjacent cells. It would be good to find out.

I am also querying whether there needs to be a change to the model, following a poster presented at the European Brewery Convention Congress in Antwerp in 2019 (34). Langenaeken and colleagues from KU Leuven and Ghent used scanning electron microscopy to firmly place β-glucan on the outside of the wall, which is diametrically contrary to all the evidence that we employed to present our wall model. Perhaps what we are seeing here relates to the two populations of β-glucan to be found in the endosperm cell walls of barley, namely gum (water-soluble) and hemicellulose (not freely soluble) (35, 36). Possibly the minor component (the gum) is surface-located and readily released during the preparation of the wall fractions that we employed, thereby exposing the pentosan layer, which in turn envelops the hemicellulosic β-glucan component. It is also interesting that Langenaeken and colleagues firmly identify pectin as a minor component of the walls and this bears greater scrutiny in the context of the solubilase story.

Fig 1 presents the original model together with a variant that would account for the surface presence of β-glucan.
In addition to the detailed look at solubilase, we have also made some forays into the other enzymes that are responsible for breaking down cell walls. Using a radial diffusion assay for endo-β-glucanase (37), we investigated this enzyme and inter alia discovered that it might be partially stabilized and made more resistant to heat by reduced glutathione (38). That the end products of β-glucan degradation in malting and mashing are oligosaccharides rather than glucose was explained by the finding that the exo-glucanases that are present and capable of yielding glucose do not do so because of a poor affinity (high $K_m$) for the products of the endo-β-glucanase action and, furthermore, these enzymes develop relatively late during germination (39).

Despite the comprehensive digestion of β-glucan during malting and mashing, it is remarkable that the arabinoxylan is largely retained and not digested. There are certainly endo-xylanases in malt (40) as well as ferulic acid esterase (41) and acetoxylan esterases (41, 42). It is suggested that a primary reason for the inefficient breakdown of the pentosans is the presence of inhibitors in the grain (40).

Finally in this topic area, we proposed an enzyme-based method for measuring pentosan (43).

**Dimethyl sulphide (DMS)**

BRF had been the centre of excellence in the study of DMS, from the initial recognition of this molecule as a key contributor to the aromas of many lager beers (44) to the excellent investigations of Harry White, who got so close to understanding the nature of the malt-derived precursors of DMS (45). White
suggested that there were two precursors located in the embryo of germinated barley, the first of which could be broken down by heat (H) (particularly under alkaline conditions, A) to yield DMS and which he called HADMS, and the second of which was present in malts cured at temperatures in excels of 75°C and that was metabolizable by yeast into DMS, hence “active HADMS”. He suggested that the former was S-methylmethionine (SMM) attached to additional peptide material but he could not identify the latter.

Dickenson (46) demonstrated that the heat-sensitive precursor was SMM per se and claimed that it did not yield any material that could be converted to DMS by yeast. However, at BRF we remained convinced that yeast is capable of producing DMS during fermentation. Brian Anness and I spent many months pondering this problem but repeatedly drew a blank when we fed yeast with a potential precursor. However, it was drawn to our attention that Zinder and Brock (47) had shown that a range of bacteria could reduce dimethyl sulfoxide (DMSO) to DMS. At the end of one of the tables of data in that paper they had also tested Saccharomyces cerevisiae and found some capability in this area. This led to our work demonstrating that yeast does indeed convert DMSO (which we showed to be present in malt, especially after curing) into DMS (48). I demonstrated that the enzyme involved was methionine sulfoxide reductase (49, see also 50). This is an enzyme present in many eukaryotes which serves the function of recycling methionine sulfoxide to methionine and thereby restoring its functionality. The reducing power is supplied by the small redox protein thioredoxin, which cycles between an oxidized (dithiol) form and a reduced (sulphydryl) form. The electrons for the reduction of the dithiol form are supplied by NADPH in a reaction catalysed by thioredoxin reductase.
Thioredoxin serves as the electron donor for a range of cellular reactions. Amongst these is the reduction of ribonucleotides to deoxyribonucleotides, the building blocks of DNA. Accordingly, if a cell is actively growing and multiplying, there is likely an a priori drain on thioredoxin to feed DNA synthesis and less available to reduce sulfoxides (51,52). This fits with our observations that DMS production by yeast was less under warmer fermentation conditions and in nitrogen-replete worts (53). We also showed that there is an inhibitor of DMSO reduction in wort and identified it as methionine sulfoxide (54). Strictly speaking, I should not call it an inhibitor, but rather an “out-competing substrate”. The $K_m$ for methionine sulfoxide for methionine sulfoxide reductase is vastly lower than that for DMSO, so if methionine sulfoxide is present it will be preferentially handled by the enzyme. This is one of the reasons why there can be more DMSO reduction in a lager fermentation than an ale fermentation, because there is more methionine sulfoxide produced at higher kilning temperatures. The other reason for higher DMS production in lagers is the lower fermentation temperature (55).

There remained many sceptics who, observing that there is vastly more DMS in pitching wort than the finished beer, could not countenance that yeast was contributing any significant quantity of DMS. However, they were losing sight of the fact that there is enormous loss of DMS with the fermenter gases. Thus the final DMS level is a balance between that in wort which is not volatilised and that which is produced by yeast from DMSO. Dupire and colleagues used labelled DMSO to show that 80% of the DMS can originate in DMSO (56). We also did labelling studies to confirm that in fermentations where there is clearly less DMS at the end than at the start, there is nonetheless DMS in the finished beer that originated in DMSO (57).

What is also evident is that certain bacteria are mightily capable of reducing DMSO to DMS (52).
A final piece of the jigsaw was our demonstration that phenyl ethanol (PE) and phenyl ethyl acetate (PEA) mask the perception of DMS in beers and the detection of DMS character is through a balance of DMS, PE and PEA (58).

Gaps? I feel that a considerable amount of work could be detected to the DMSO reduction story. I think there remains more to discover about why the gene for the enzyme is expressed to a greater degree at lower fermentation temperatures, why more DMS is produced at higher pitching wort gravities and also at higher pH (52).

**Flavour**

In my laboratories in UC Davis we pursued several other studies on flavour issues, including the study of sulphur volatiles in addition to DMS (59). It seems to me that much more necessary information remains to be discovered about the control of some of these volatiles, notably the thiols and the mercaptans. However, there needs to be further delving into the production of methyl thioacetate, which Kanauchi and I showed to be produced by alcohol acetyl transferase, the same enzyme from yeast that yields the esters (60).

Donaldson et al (61) made some of the earliest inroads into establishing a meaningful lexicon to describe hop aroma. In relation to hop variety, there are some who suggest that one of the impacts on hop
aroma is the release of flavoursome substances (aglycones) from a binding to sugar. It has been suggested that this is effected by β-glucosidases from yeast, although Kanauchi and I found these to be intracellular (62).

Meanwhile, a degree of clarity was brought to the diversity of enzymes in ale and lager yeasts that are responsible for reducing diacetyl during fermentation and maturation, with a greater degree of complexity in lager yeast (63). Of course, for the longest time prolonged maturation of lager-based beers has been advocated, in part (but not entirely) to mop up the last traces of vicinal diketones and acetaldehyde. From the days of his employment within a brewing company that did not see the merits of prolonged aging of beer, the present author has been sceptical of its necessity. Laura Metrulas and colleagues used metabolomics to illustrate our inability to find significant changes in non-volatile molecules in beers during prolonged storage (64). [We had previously explored the use of this technique to address impacts of later and dry hopping (65).] I am extremely respectful of the fact that there are many who insist that prolonged lagering is beneficial, basing their conclusions on their own sensory perceptions. I am equally clear that we only examined a relatively narrow range of storage conditions. I insist that this territory represents a vast seam of research potential, insisting that it needs to be a combination of meticulous and detailed analytical chemistry with robust organoleptic approaches.

In the writing of this paper I was intrigued to find an account by Horace Brown of his findings on a tour to the United States (66). In discussing the production of lager beers, he referred to an accelerated process (vacuum-based) and made the following observation:
That a perfectly sound and saleable article can be produced by the vacuum system is an undeniable fact, but whether the longer storage and maturation of the beer brewed on the old system does not produce certain high class qualities which are lacking in the more quickly made and less matured vacuum beers can only be determined by a lengthy trial and by the competition of trade, which can alone decide which of the two is the fitter for survival. At present I hold my judgment on this question in suspense.

Flavour instability

Although we showed how brand identity can seriously confuse the perception of beer freshness (67), I remain convinced that the achievement of flavour-stable beer is the last major technical challenge facing brewers, important because staling for most beers seriously detracts from their drinkability.

Roy Parsons and I were the first to draw meaningful attention to a role for reactive oxygen species as a key underpinning cause of oxidative damage to wort and beer (68). In the pursuit of understanding how the development of such radicals could be prevented, we investigated a number of enzymes, notably superoxide dismutase (69, including soy beans as a source of a particularly heat-tolerant version of this enzyme, 70), catalase and peroxidases (71, 72, 73, 74, 75). Our work also highlighted to significance of minimizing the levels of certain metal ions in wort and beer, notably iron and copper (76, 77, 78, 79, 80, 81) and, as we later confirmed, manganese (82). In contrast to the focus of many, I have questioned the relative significance of lipoxygenase to flavour instability (83, 84).
Investigations over many years reinforced my opinion that flavour stability is a problem that should be addressed commercially “in reverse order”, with a focus on beer in the trade first and then tracking back (85, 86, 87). Thus, I am at pains to emphasize absolutely that the two most important considerations should be the minimization of oxygen in the final package and the maintenance of beer at the lowest possible temperature (short of freezing) throughout storage and distribution. Only once this is assured is it worth paying attention to points upstream.

Mindful of the fact that many researchers are emphatic in their beliefs that there is much that can be done upstream to improve shelf life, I have felt it important to reemphasize the opinion first voiced by Meilgaard (88), that so much of the research on the sensory attributes of beer in relation to aging is substandard. To that end, I emphasize that the yardstick for flavour stability should be time to a detectable flavour change and not intensity of flavour change (89, 90). I am fully aware that I can be criticised for not having adhered to this in my earlier researches.

It is unquestionably the fact that oxygen is consumed upstream. Oxygen entering mashes causes an increase in colour, an attendant decrease in polyphenol levels, an increase in haze, reduced rates of wort separation and a decrease in the level of free thiols (91). In relation to this, our discovery of ascorbate peroxidase (92) and especially ascorbate oxidase (93) in malt has relevance. By the addition of ascorbate to mashes, the latter enzyme, which is remarkably heat resistant, can preferentially scavenge the oxygen and make for less thiol oxidation, less colour and higher polyphenol levels in the wort. For those convinced that brew house oxidation is important for flavour stability, herein lies one approach that is very much deserving of a lot more research. I also suggest that there is more to be done to build on the initial studies on other oxidases, notably oxalate oxidase (94) and thiol oxidase (95). In passing I
note that we suggested that a depletion of thiol oxidase during the storage of freshly kilned malt is a
causative factor in the attendant improved brewhouse performance of that malt.

**Foam**

We can be confident that foam truly is a critical determinant of beer quality (96, 97, 98). We can be just
as sure that problems with beer foam are far more likely to arise in the bar than in the brewery (99).
Nonetheless it is critical that we have the fullest possible understanding of the chemistry and physics of
beer in relation to foaming properties (100, 101, 102, 103).

Philip Slack and I used hydrophobic interaction chromatography to draw attention to hydrophobicity as
a key feature of the polypeptides that afford the most stable foams (104). Subsequent studies showed
that the proteins in the albumin fraction from the grain have more foam stabilizing capability than those
that are derived from hordeins through partial hydrolysis (105), although the latter appear to have
greater capability to enter into foam, thereby interfering with the ability of proteins such as lipid
transfer protein and Protein Z to exert their stabilizing influence (106). This is a field of inquiry well
worthy of further investigation, the logistical inference being that removal of hordein-derived fragments
should lead to superior foaming performance in a beer. That would suggest that the enzyme prolyl
endoproteinase, employed both as a haze-preventing agent and in the production of gluten-free beers,
might actually be expected to **improve** foam stability. The observations made thus far in this area are
contradictory (103).
Beer is, of course, a complex matrix and a plethora of substances can alternatively stabilize or inhibit foam (107, 108). One of the challenges is in relating studies made in model systems, using isolated or even non-native materials such as exogenous polypeptides, to what happens in beer poured into a glass. An example is pH, where a decrease in pH in the range 4.0 to 4.5 can variously lead to an increase or a decrease in perceived form performance (108, 109).

The reality is that foam is an extremely complex phenomenon, with the net foam performance attendant upon very many variables, both chemical and physical (110). Furthermore, the manifestation of foam is complex, with diverse aspects to it, including formation (nucleation or beading, which we modelled, 111), retention (stability), texture and colour, and lacing (cling). Small wonder that a range of methods have been proposed for measuring foam, several which we have evaluated (112, 113, 114).

In terms of our own method development, Gordon Jackson and I long ago developed the lacing index procedure and applied it to assess some of the factors that influence the clingability of foam (115, 116).

I maintain, however, that the route to solving foam issues lies in the availability of robust methods to allow the investigator to determine whether a deficiency in perceived stability is due to a shortage of foam positives, presence of foam negatives or both. Chandley and I developed a test for assessing the level of foam positive polypeptides in beer (117). It was marketed commercially by BRFI and involves measuring protein in beer before and after removing the hydrophobic polypeptides on tiny columns of phenyl sepharose. The decrease in protein indicates the total amount of hydrophobic (foam-positive) polypeptide present. The problem is that there is a substantial amount of protein in beer and thus there
is a subtraction of two relatively large numbers to yield a rather smaller one, with the attendant
imprecision entailed. Nonetheless, others have used it to good effect. We did attempt to develop a
fluorescence-based approach to assessing hydrophobic polypeptides (118).

Rather more promising in my opinion are the approaches originally developed by Roy Cope and I (119, 120; see also 121) and Kamini Dickie et al (122), both of which were explored in more detail by Goldberg and Bamforth and myself (123). The first of these involves the addition of egg albumin to beer, ultrafiltered beer and to a control alcohol solution to ascertain whether there is a shortage of polypeptide or the presence of foam negative material. The second approach is the passage of beer through a column containing lipid binding protein, the argument being that an increase in foam stability attendant upon this treatment is indicative of there being foam inhibitors in the beer.

In our work we were able to demonstrate that many commercial beers contain substantial levels of foam-negative materials. The likeliest source of these is the grist. We showed that there is foam negative materials in all malts, and that the net contribution that these malts make to foam performance is a balance between their level of foam-negative materials and foam-positive materials (124, 125). Thus, we confirmed the long-standing view that wheat is a superior source of foam-positive material than is barley (124). However, we were surprised to find that, contrary to established dogma that crystal malts were foam-positive, they in fact can contain significant amounts of foam-negative materials, at least some of which were oxidized fatty acids (125). The intriguing thing is that the crystal malt possessed of the most foam-negative material gave beer with better foam stability than the crystal malt that contained less foam-negative material (124). I suggest the following explanation, something else worthy of further investigation: the foam-negative material from the crystal malt serves as an anti-
foam during fermentation. As such, it serves to preserve foam-positive material in the beer. Provided
the foam-negative material is removed downstream (e.g. by filtration), the ensuing foam performance in
the beer is superior. If, however the foam-negative material survives into the beer, it is damaging to
foam performance in the glass.

Combe et al (124) confirmed that the best foam performance of all is from heavily roasted grain.
Subsequently Emily Kultgen, Makoto Kanauchi and I demonstrated that the foam stabilising material
from black malt is a very small molecule, featuring some peptide material and pyridyl entities produced
during the roasting process (126). There is huge scope for further research here, as this material could
represent a wonderful foam-promoting addition if it can be successfully separated from the coloured
entities.

Beer, health and perceptions

One area that others in the brewing industry have been less than comfortable in me pursuing is that of
beer (in moderation) as a component of a healthful lifestyle. The issue was not that they did not believe
it to be true, but rather that the perception would be that a scientist working within the industry could
not take a dispassionate approach to the matter. I have been assiduous in not using industry funds in
any of my work and I have always been at pains to emphasize negatives as well as positives as I sought
to (at the least) illustrate how beer is more than the equal of wine, for which beverage there seems not
to have been the same reluctance to hold back (127-137). We have highlighted how wine is (incorrectly)
perceived as a healthier option (138, 139). We have also highlighted the ignorance concerning matters
of beer and brewing that many people have (140). There should be no let-up in the education of the drinking public.

In terms of specific research on health-related issues concerning beer, then we have included studies on antioxidants (141), folate (142), minerals (143) especially silicate (144), as well as soluble fibre and prebiotics as referred to earlier. Furthermore, we have explored the gliadin content of commercial beers (145) and highlighted the merit of the enzyme prolylendoproteinase in producing gluten-free beer (146). We employed an ELISA-based procedure to measure gliadin. There are those who insist that it is insufficiently sensitive and are critical of its use in beer. This area needs extensive research, including studies in conjunction with those in the medical profession.

We also did not fight shy of the matter of carbohydrates in beer in relation to health, discussing the nonsense of the beer belly and the glycaemic index as it pertains to beer (147).

**Downstream processing and haze**

Bizarre as it may seem in the current climate of turbid beers, our researches have from time-to-time dwelled on aspects to do with enhancing the colloidal stability of beer (148, 149). Indeed, one study from 2007 demonstrated that there was a clear preference for bright beer over even the most marginal of turbid brews (150). Perhaps such a study at the current time would yield a different outcome?
Of particular significance was the work of Michaela Miedl and I, in which we demonstrated that the key to precipitation of material in cold stabilization procedures is the lowness of the temperature rather than the time of storage (151). We also pursued model systems to extend the seminal work of Siebert on chill haze (152). Other relevant research concerned the efficiency of polyphenol adsorbents (153, 154), including the demonstration that PVPP has no impact on the flavour stability of beer (155). Finally, we identified unmodified barley endosperm as one of the causes of invisible hazes in beer – simultaneously failing in our efforts to get these problems referred to as “pseudo haze” (156).

Colour

My contributions to the matter of beer colour have included demonstration of the confusion that can arise in the non-trained taster’s perceptions of flavour if the colour of a specific beer is modified (157), as well as confirming the weakness of colour methodology based on a single wavelength (158).

Ions and pH

Whilst it is customary to approach brewing and beer on a process or product basis, e.g. mashing, yeast, foam, stability etc, it can also be useful to address matters based on chemistry per se. For example, the approach taken in the review of matters of ionic equilibria and pH, influencing as they do diverse aspects of process and product performance (159, 160). There is much more scope for this approach.
Apart from failing to confirm the suggestion made elsewhere that limit dextrinase can be released in an active form by the thioredoxin system (161), my solitary contribution in the starch field has been a review (162). This certainly does not mean that I feel the area to be unfruitful. I believe, for example, that there is an urgent need to understand the interaction between barley variety, extent of modification and temperature in relation to starch gelatinization.

Genetic modification

While I was Director of Research at BRF International in the 1990’s, John Hammond and his team made the pioneering studies into securing approval for the world’s first genetically modified brewing yeast and we also explored opportunities for improving other brewing raw materials, notably barley (163, 164). I have long been convinced that sizeable take-up of genetically modified organisms in brewing would be dependent on there being a genuine and incontrovertible benefit for the customer and environment. More recently we were associated with our sister campus, UC Berkeley, in their development of yeasts that express genes that generate interesting flavours (165). There has already been commercial take up of some of these strains, one of the arguments in favour being that they may lower the environmental footprint of certain crops.

Microbiology
Regarding matters microbiological, then Nick Bokulich made an extensive contribution in his time in my laboratory (166, 167, 168). Of note was the extensive examination of the evolution of the diverse microflora in the production of “wild” beers (169). In relation to the production of sour beers, one interesting approach would be the use of a single organism capable of producing both alcohol and souring quantities of acid, such as Lachancea (170).

Enzymology

As someone who emerged from his graduate studies as an enzymologist, it is perhaps no surprise that much of the research referred to above is at the enzyme level. In terms of generalities of enzymes in brewing, then go to references 171-178.

Business of beer

I started this discourse by emphasizing matters of project selection and the imperative of ensuring relevance in one’s research focus. It is essential for anyone intent on pursuing brewing research to understand the business and its trajectories. I have been fortunate to be in collaboration with Ignazio Cabras on such matters (179, 180).
When I first joined the brewing industry in 1978 there are many things I would not have predicted: the growth of the (so-called) craft sector; the love of immensely turbid beers; beers possessed of bizarre ingredients; the degree of in-line sophistication; and more. However, the fundamental brewing paradigm of barley-malt-milled malt-mash-lauter-boil-clarify-cool-ferment-mature-stabilize-package has remained unaltered. From time to time I have suggested alternatives (6, 181, 182, 183, 184, 185). I find it very hard to ever countenance beer being produced from a bland alcoholic base (186), despite its potential environmental advantage (187). However in an era when there is such interest in hard seltzers...quo vadis?

References


https://doi.org/10.1042/bj1910863


https://doi.org/10.1080/00960845.1955.12006443


https://doi.org/10.1002/j.2050-0416.1972.tb03472.x


http://dx.doi.org/10.1094/CCHEM.2001.78.2.121


https://doi.org/10.1016/j.enzmicrotec.2005.01.009


https://doi.org/10.1002/j.2050-0416.2003.tb00168.x


https://doi.org/10.1002/j.2050-0416.2008.tb00316.x


Fig 1. Models for the cell wall of barley. (a) the model after Bamforth and Kanauchi (30); (b) a revised model to account for the presence of soluble β-glucan on the surface of the walls. In either case it should be realised that the various layers represent long-chain fibrous molecules that have a degree of porosity and are not “solid walls”. It is likely that there is intermingling of the various polymers.
(a) 

β-glucan

Arabinoxylan

Proteinaceous middle lamella

(with ferulate and acetate attached)

(b) 

Hemicellulosic β-glucan

Gum β-glucan

Arabinoxylan

Proteinaceous middle lamella