Research Article

Received: 3 July 2009 Revised: 28 November 2009 Accepted: 1 December 2009 Published online in Wiley Interscience: 8 February 2010

(www.interscience.wiley.com) DOI 10.1002/jsfa.3884

Silicon in beer and brewing

Troy R Casey and Charles W Bamforth*

Abstract

BACKGROUND: It has been claimed that beer is one of the richest sources of silicon in the diet; however, little is known of the relationship between silicon content and beer style and the manner in which beer is produced. The purpose of this study was to measure silicon in a diversity of beers and ascertain the grist selection and brewing factors that impact the level of silicon obtained in beer.

RESULTS: Commercial beers ranged from 6.4 to 56.5 mg L^{-1} in silicon. Products derived from a grist of barley tended to contain more silicon than did those from a wheat-based grist, likely because of the high levels of silica in the retained husk layer of barley. Hops contain substantially more silicon than does grain, but quantitatively hops make a much smaller contribution than malt to the production of beer and therefore relatively less silicon in beer derives from them. During brewing the vast majority of the silicon remains with the spent grains; however, aggressive treatment during wort production in the brewhouse leads to increased extraction of silicon into wort and much of this survives into beer.

CONCLUSION: It is confirmed that beer is a very rich source of silicon.

Keywords: silicon; beer; barley; malt; hops; silica hydrogel; diatomaceous earth; brewing

INTRODUCTION

The dietary intake of silicon in the USA is about 20–50 mg day^{-1} $person^{-1}$, with younger adults and males consuming the highest amount.[1–3] Silicon impacts bone mineral density in humans[4,5] and supplementing silicon in the diets of women with osteoporosis increased bone mineral density.[6] Silicon increases type I collagen synthesis and promotes the differentiation of osteoblast-like cells.[7] It also helps protect the human body from the toxic effects of aluminium.[8]

Silicon has been shown to be prevalent in the husk of whole grains,[9] including barley, wheat bran, oats and rice bran[2,10] and, accordingly, foods incorporating such materials tend to be rich in silicon (Table 1). Bananas are rich in silicon, having 5.44 mg of silicon per 100 g portion, but only about 5% is bioavailable.[1] Silicon is present in beer in the soluble form of orthosilicic acid[4] in which form there is $>50\%$ bioavailability.[11,12] Beer, due to its high level of silicon in this form, has been claimed to be a major contributor to the overall silicon intake in the Western diet.[1,2] In 76 beers from the United Kingdom, mainland Europe, and Asia, the average silicon content was 19.2 ppm with a standard deviation of 6.6 ppm and a range of 9.0–39.4 ppm.[12] There was seemingly no correlation between style, location or presentation of the beers. Another study of 60 international beers revealed average silicon content of 18.7 ppm with a range of about 10–40 ppm.[13] Again, no relationships were reported to different beer styles.

The factors in brewing that influence silicon levels in beer have not been extensively studied. It was found that silicon extraction increased with respect to the specific gravity of the wort during sparging of grain in the separation of wort from spent grains after mashing, when the pH of the mash starts to rise.[14,15]

In this paper we have examined a wide range of beer styles for their content of silicon and have also studied the impact of raw materials and the brewing process on the quantities of silicon that enter wort and beer. This substantially builds upon a prior report that is more limited in scope.[15]

MATERIALS AND METHODS

Materials

Malt samples were from Briess Malt and Ingredients Company (Chilton, WI, USA), Cargill (Sheboygan, WI, USA) or Great Western Malting (Vancouver, WA, USA). Pelleted hops were from John I Haas (Washington DC, USA). Water treatment salts were from Crosby and Baker (Westport MA, USA). American Ale Yeast 1056 was from Wyeast (Odell, OR, USA). Filter pads were from Gusmer Enterprises (Mountainside, NJ, USA) and were Cellupore grade 19455D. Diatomaceous earth was from Genencor (Rochester, NY, USA). Silica hydrogel was Crosfield Chill-Garde (INEOS Silicas Americas, Joliet, IL, USA)

Measurement of silicon

All samples were collected and prepared using polypropylene or polyethylene laboratory apparatus and were frozen prior to analysis. They were analyzed for silicon at the University of California Agriculture and Natural Resources Analytical Laboratory,

* *Correspondence to: Charles W Bamforth, Department of Food Science & Technology, University of California, Davis, CA 95616-8598, USA. E-mail: cwbamforth@ucdavis.edu*

Department of Food Science & Technology, University of California, Davis, CA 95616-8598, USA

Table 1. Average content of dry silicon in some foods

Food	Si (mg 100 g^{-1})
Granola cereal	12.25
High fiber wheat bran cereal	11.42
Oat bran	23.36
Porridge oats	11.39
Dates (dried)	16.61

Data sourced from Powell *et al.*[18]

Davis, California (danranlab.ucanr.org). Solid samples were measured using the method of Feng *et al.*[16] This method measures the silicon concentration of solid matter using a nitric acid, hydrogen peroxide and hydrofluoric acid digestion followed by analysis by inductively coupled plasma–atomic emission spectrometry (ICP–AES). This method is reproducible within 8%. Liquid samples were analyzed using the method of Meyer and Keliher.[17] The method is also reproducible within 8%. In our measurements on beer, all values fell within a standard deviation of 2.6. Additional precision data is offered in the footnotes to some tables.

Commercial samples

One hundred commercial beers were obtained from a local grocery store. Each sample was degassed in a 2 L vacuum flask for 3 h under a vacuum of 137.8 kPa (20 lb/in^2). Sixty milliliters of each sample was submitted for analysis.

Ingredients and process aids and their analysis for silicon

Malts were ground following the American Society of Brewing Chemists standard method Malt 4 and dried at 102 °C for 3 h prior to analysis as above. Hops were dried at 102 °C for 3 h prior to analysis.

To test whether or not silicon can be extracted from diatomaceous earth (DE), a popular commercial American lager beer was spiked with DE at a rate of 100 g DE hL^{-1} hectolitres (HL) beer with incubation for 5, 10, 20 or 30 min with gentle stirring. All tests were done at 1 °C. Samples were then gravity filtered though an Ahlstrom (Groesbeck, TX, USA) grade 509, 32 cm circle filter and the filtrate analyzed for silicon.

To determine if any silicon is extracted from silica hydrogel that is sometimes used to stabilize beer, 0.075 g of Crosfield Chill-Garde was added to 500 mL of maturing beer from the UC Davis pilot brewery and shaken vigorously for 1 min. The sample was then held at 4 °C for 24 h and the supernatant analyzed for silicon.

Trial brewing

All brewing was performed in the University of California, Davis Pilot Brewery.

In the profile of each brew, the terms 'gentle lautering' and 'vigorous lautering' are used to describe the amount of force added to the brew during the lauter tun operation. A gentle lautering is one where no extra force is added to the mash during the wort separation process. That means the mash bed is not disturbed at all during the separation of the liquids from the solids. This would be considered the best-case scenario for a commercial brewery. A vigorous lautering is one where much external force is added to the mash in the lauter tun in the form of raking. For these brews where a vigorous lautering was desired, the mash was consistently agitated or raked for the duration of the process. This mimics a worst-case scenario in a commercial brewery.

Brew 1

The targets for this brew were 151 L of 10°Plato wort with 15 bitterness units. The raw materials used were malt (22.4 kg), water (87.2 L), treatment salts (116 g) and hop pellets (60.4 g). Mashing was at 65 °C for 45 min, and then the temperature was ramped to 77 °C and held for 5 min. The mash was transferred to the lauter tun and the wort re-circulated for 10 min. A gentle lautering was performed. The wort was boiled for 45 min with the hops added at the start of the boil. The wort was transferred to the whirlpool and held for 15 min. The wort was cooled to 17.8 °C in a counter-flow heat exchanger using water and glycol and transferred to the fermenter. Medical grade compressed air was added during this transfer to the point of saturation. The fermenter was set to 20.0 °C. Yeast (1.56 L) was added to the fermenter for a pitching rate of 1 million cells mL^{-1} (degree Plato)$^{-1}$. The yeast was removed from the bottom of the fermenter after 12 days. The beer was transferred to a conditioning tank and the temperature was set to 5 °C. After 2 days the beer was filtered.

Brew 2

The brew was identical to the first brew with the exception that mashing was for 100 min, and fermentation was for 8 days.

Brew 3

This brew was similar to brews 1 and 2 but taken only as far as the sweet wort stage. Mashing-in was at 50 °C with a 20 min stand before ramping to 65 °C over a 15 min period and holding for 55 min. Thereafter it was ramped to 77 °C for 10 min and held for 5 min before transferring to the lauter tun with recirculation for 10 min. After the transfer a very vigorous lautering was performed. The wort was transferred to the brew kettle until 151 L were collected.

RESULTS AND DISCUSSION

Levels of silicon in commercial beers and the raw materials from which they are derived

One hundred commercial beers were analyzed for silicon content and the data collated according to beer style and source (Table 2). The average silicon content of these beers sampled was 29.4 ppm. This value is much higher than those found in the studies referenced above. This may be due to the more extensive sample set drawn from smaller independent breweries that tend to use higher proportions of malt, which equates to more silicon added to the process (cf. Table 3).

The India Pale Ale (IPA) category is traditionally a stronger and hoppier beer, ergo one with a higher charge of malt and hops (cf. Tables 3 and 4) and hence more silicon. By contrast, wheat-based beers contain less silicon, which seems to be related to the lower levels of silicon in wheat malt (Table 5). Additionally, wheat beers are produced with much less hops than many other beer styles. Light lagers usually derive from high adjunct grists, such as corn, and it was found that light beers contained less silicon.

There is as yet no recommended daily intake level for silicon. However, on the basis of the average daily intake of 20–50 mg, then it can be inferred from Table 2 that, on average, 2 L of beer will satisfy that, with 1 L of some beers providing the higher level of intake.

Table 2. Silicon content of commercial beers

Category	Si, average (ppm)	Range (ppm)	*N*
All	29.4	6.4–56.4	100
Ales	32.8	11.1–55.5	67
Lagers	23.7	10.1–56.4	27
Regular lagers	23.8	14.5–40.4	9
Light lagers	17.2	14.1–23.4	5
IPA	41.2	26.2–55.5	15
Non-alcoholic	16.3	6.4–25.7	6
Wheat	18.9	14.3–23.4	7
Pale ale	36.5	16.8–50.7	18
Sorghum	27.3	23.9–30.7	2
USA	31.6	11.1–56.4	80
International	20.4	6.4–40.4	20
California	34.2	11.1–56.4	50
Colorado	20.8	14.1–26.2	10

Table 3. Silicon content of barley and malt

Sample	% Si dry weight
Tradition barley	0.26
Tradition malt	0.24
Robust barley	0.24
Robust malt	0.23
Lacey barley	0.22
Lacey malt	0.26

Duplicate measurements were within ±0.01%.

Table 4. Silicon content of hops

Sample	% Si dry weight
Centennial	0.86
Willamette	1.00
Tettnang	0.94
Cascade	0.86
Millennium	0.79
Nugget	0.47

Duplicate measurements were within ±0.02%.

There is little change in the silicon content of barley during the malting process (Table 3). The majority of the silicon in barley is in the husk, which is not affected greatly during malting. The malts with the higher silicon contents are pale-colored products (carapils, 2-row, pilsen, and crystal 20 and 120; Table 5) which have less heat stress during the malting process. The darker products, such as the chocolate, roasted barley and black malt, all have substantial roasting and much lower silicon contents than the other malts for reasons that are not yet known.

The hop samples analyzed showed surprisingly high levels of silicon with as much as four times more silicon than is found in malt (Table 4). However, hops are invariably used in a much smaller quantity than is grain. Highly hopped beers, however, would be expected to contain higher silicon levels.

Table 5. Silicon content of malts

Sample	% Si dry weight
Carapils	0.20
White wheat malt	<0.01
Chocolate malt	0.10
Crystal 20	0.24
Crystal 120	0.19
Pilsen malt	0.17
Roasted barley	0.12
2-row	0.20
Black malt	0.08

Duplicate measurements were within ±0.01%.

Table 6. Silica xerogel silicon analysis

Sample	Si (ppm)*
Silica gel test	19
Silica gel control	20

* Duplicate measurements were within ±1 ppm.

Table 7. Diatomaceous earth (DE) silicon analysis

Sample	Si (ppm)*
Beer alone	21.6
Filtered beer	21.9
5 min w/DE	21.8
10 min w/DE	21.7
20 min w/DE	21.8
30 min w/DE	21.6

* Duplicate measurements were within ±0.1 ppm with DE.

No silicon was picked up from silica hydrogel used to stabilize beer, even after a period of 24 h (Table 6) and neither is there pick-up from diatomaceous earth filter aid (Table 7).

Mass balance of silicon through the brewing process

Several brews were pursued in an experimental brewery to evaluate the mass balance of silicon through the process. In a study of this nature there are invariably some sampling challenges. This leads to a certain degree of variability in the calculated quantities.

Trial brew 1 (Fig. 1) consisted of a gentle 45-min mash with a gentle lautering process. The majority of the silicon entering the mash from the malt emerged with the spent grains. Hops introduced approximately 14% of the silicon at the boiling stage, but more silicon is removed on the precipitate (trub) formed during boiling than enters with the hops. At the fermentation stage the silicon introduced with the yeast is in balance with that leaving with the surplus yeast.

Trial brew 2 (Fig. 2) consisted of a gentle prolonged 100-min mash with a gentle lautering process. Within the inherent sampling errors described earlier, there are no significant differences in silicon distributions as compared to brew number 1.

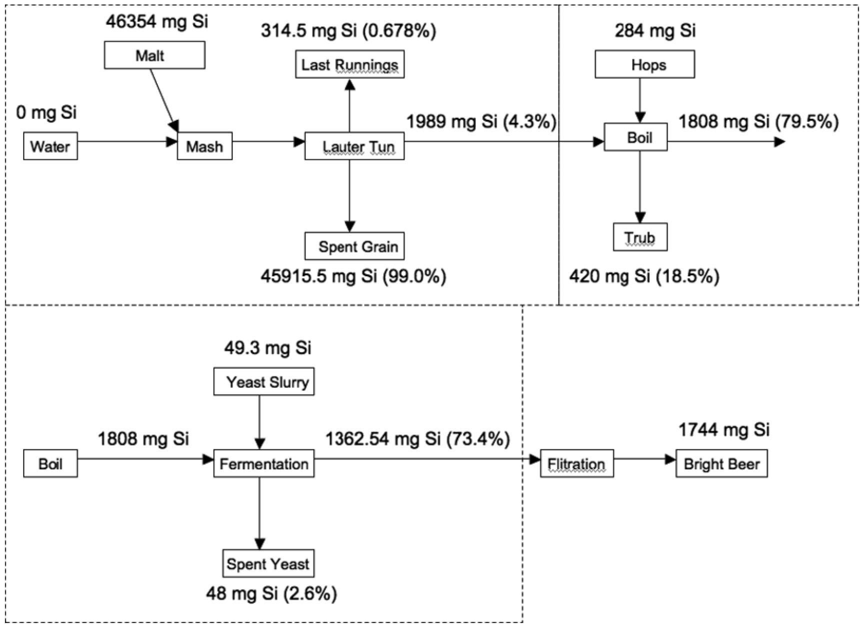

Figure 1. Trial brew 1.

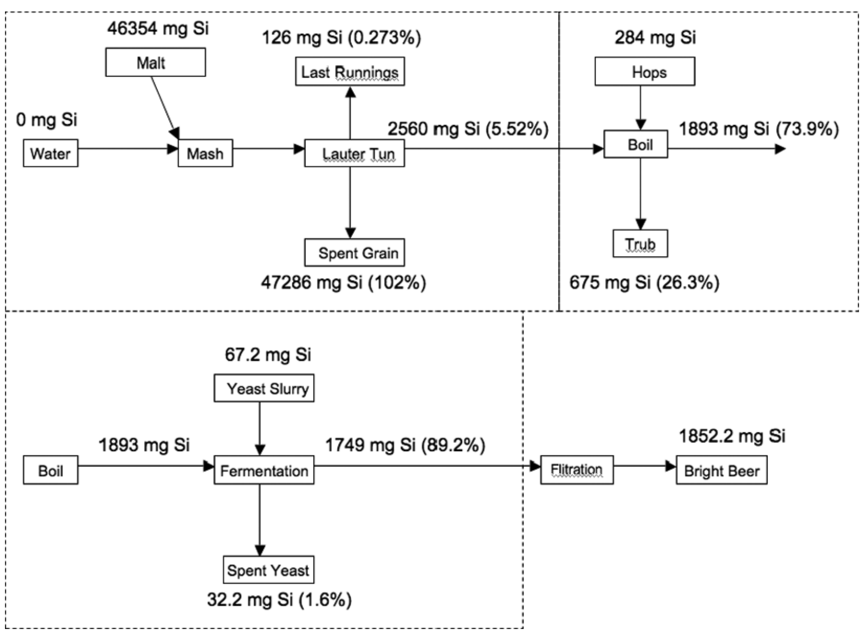

Figure 2. Trial brew 2.

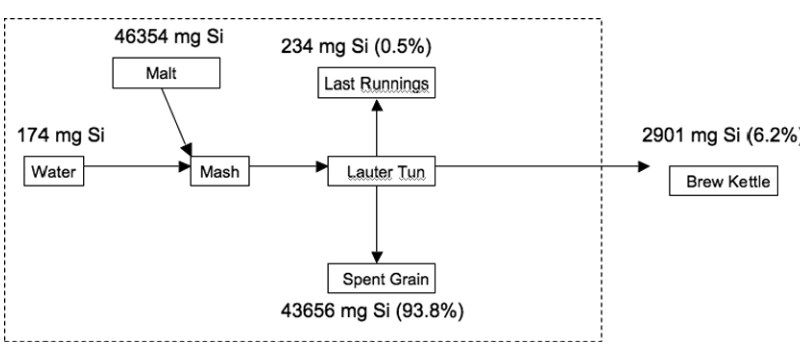

Figure 3. Trial brew 3.

Trial brew 3 (Fig. 3) consisted of a gentle 100-min mash but with a vigorous lautering process. The brew was not advanced past the completed lautering step. It appears that there is a slightly enhanced delivery of silicon into the wort in this instance.

CONCLUSIONS

Beer is a substantial source of silicon in the diet. Beers containing high levels of malted barley and hops are richest in silicon. Wheat contains less silicon than barley because it is the husk of barley that is rich in this element. Most of the silicon remains in the husk during brewing, but significant quantities of silicon are extracted into wort and these substantially survive into beer.

ACKNOWLEDGEMENTS

We thank Dirk Holstege for his valuable input.

REFERENCES

1 Jugdaohsingh R, Anderson SHC, Tucker KL, Elliott H, Kiel DP, Thompson RPH, *et al*, Dietary silicon intake and absorption. *Am J Clin Nutr* **75**:887–893 (2002).
2 Pennington JAT, Silicon in foods and diets. *Food Addit Contam* **8**:97–118 (1991).
3 Uthus EU and Seaborn CD, Deliberations and evaluations of the approaches, endpoints and paradigms for dietary recommendations of the other trace elements. *J Nutr* **6**:2452S–2459S (1996).
4 Jugdaohsingh R, Tucker KL, Qiao N, Cupples LA, Kiel DP and Powell JJ, Dietary silicon intake is positively associated with bone mineral density in men and premenopausal women of the Framingham offspring cohort. *J Bone Mineral Res* **19**:297–307 (2004).
5 Tucker KL, Kiel DP, Powell JJ, Qiao N, Hannan MT and Jugdaohsingh R, Dietary silicon and bone mineral density: the Framingham Study. *J Bone Mineral Res* **19**:276–281 (2001).
6 Eisinger J and Clairet D, Effects of silicon, fluoride, etidronate and magnesium on bone mineral density: a retrospective study. *Magnesium Res* **6**:247–249 (1993).
7 Reffitt DM, Ogston N, Jugdaohsingh R, Cheung HF, Evans BA, Thompson RP, *et al*, Orthosilicic acid stimulates collagen type 1 synthesis and osteoblastic differentiation in human osteoblast-like cells *in vitro*. *Bone* **32**:127–135 (2003).
8 Gonzalez-Munoz MJ, Meseguer I, Sanchez-Reus MI, Schultz A, Olivero R, Benedi J, *et al*, Beer consumption reduces cerebral oxidation caused by aluminum toxicity by normalizing gene expression of tumor necrotic factor alpha and several antioxidant enzymes. *Food Chem Toxicol* **46**:1111–1118 (2008).
9 Broadhurst L, Silicon's elemental benefits. [Online]. Available: http://www.prolithic.com/hpages/ref_docs/orthosil.html [26 June 2009].
10 Schwarz K and Minle DB, Growth-promoting effects of silicon in rats. *Nature* **9**:333–334 (1972).
11 Bellia JP, Birchall JD and Roberts RB, The role of silicic acid in the renal excretion of aluminum. *Ann Clin Lab Sci* **26**:227–233 (1996).
12 Sripanyakorn S, Jugdaohsingh R, Elliott H, Walker C, Mehta P, Shoukru S, *et al*, The silicon content of beer and its bioavailability in healthy volunteers. *Br J Nutr* **91**:403–409 (2004).
13 Walker C, The silicon content of German beers and its potential health implications. *Brauwelt Int* **21**:173–174 (2003).
14 Anderson IW, Molzahn SW, Roberts NB, Bellia J and Birchall JD, Origin and physiological role of beer silicon, in *Proc Eur Brew Conv Cong, Brussels*, IRL Press, Oxford, pp. 543–551 (1995).
15 Walker C, Freeman G, Jugdaohsingh R and Powell J, Silicon in beer: origin and concentration, in *Beer in Health and Disease Prevention*, ed. by Preedy VR. Academic Press, Burlington, MA, pp. 367–371 (2009).
16 Feng X, Wu S, Wharmby A and Wittmeier A, Microwave digestion of plant and grain standard reference materials in nitric and hydrofluoric acids for multielemental determination by inductively coupled plasma mass spectrometry. *J Anal At Spectrom* **14**:939–946 (1999).
17 Meyer GA and Keliher PN, An overview of analysis by inductively coupled plasma–atomic emission spectrometry, in *Inductively Coupled Plasmas in Analytical Atomic Spectrometry*, ed. by Montaser A and Golightly DW. VCH Publishers, New York, pp. 473–516 (1992).
18 Powell JJ, McNaughton SA, Jugdaohsingh R, Anderson SH, Dear J, Khot F, *et al*, A provisional database for the silicon content of foods in the United Kingdom. *Br J Nutr* **94**:804–812 (2005).

