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OPERATIONAL CONSIDERATIONS FOR HOT-WASHING IN POTATO CRISP MANUFACTURE

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Abstract

As part of an overall programme aimed at reducing the acrylamide content of crisps, this paper explores the impact of hot-washing on potato slice sugar concentration during industrial scale manufacture. We investigated cold-washing as an alternative to hot-washing, hot-wash residence time and temperature to optimise sugar removal and therefore reduce the potential for high acrylamide levels after frying. Due to the variable nature of potatoes, an extensive variability study was performed to determine confidence boundaries of results. It was found that the cold-wash unit removed on average 21% of the initial sugar content. In the hot-wash the current operational residence time of 3.5 minutes at 70°C gave a sugar reduction of 27.5%, which could be increased to 48.5% if residence time is extended to 5 minutes. Hot-wash temperatures of 40°C - 60°C were found to increase glucose and fructose content and therefore the potential for acrylamide formation. A "double cold-wash" was trialled and proved to be as successful as hot-washing at 70°C for all but the highest sugar potatoes, challenging the current operational process and offering the potential for major energy savings.

Key Words: Crisp Manufacture, Blanching, Reducing Sugars, Food Processing, Acrylamide.

1. Introduction

The International Agency for Research on Cancer have classified acrylamide as potentially carcinogenic (International Agency for Research on Cancer, 1994). Acrylamide is produced in the Maillard Reaction (MR) when potatoes are heated to high temperatures (Knol, 2005; Mottram *et al*, 2002), which in crisp manufacture occurs in the frying unit. The current benchmark level of acrylamide in potato crisps is 750 ppb (European Commission, 2017). Commission Regulation (EU) 2017/2158 of 20 November 2017 establishing mitigation measures and benchmark levels for the reduction of the presence of acrylamide in food.

A toolbox describing methods to reduce acrylamide in food was published by FoodDrinkEurope in 2019 which states that for sliced potato crisps, hot-washing is actually counterproductive and although it removes some sugars (and therefore reduces acrylamide potential), it results in loss of flavour and texture and increase in oil content (FoodDrinkEurope, 2019). Palermo *et al* (2016) described studies considering the practicality and impact of suggestions from the prior version of the Acrylamide Toolbox (2013) to confirm the negative impacts on quality.

Given the increasing focus on acrylamide in food products, this paper describes a study focused on assessing the effectiveness of sugar, and in particular, reducing sugars, removal in an industrial hot-wash unit. Sugar reduction is an important processing step, as reducing sugars such as glucose and fructose, together with amino acids such as asparagine are acrylamide precursors (Knol, 2005) and can impact on its production during the frying process (Wickland, 2006). The removal of reducing sugars in hot-washing at 50^{o}C has already previously been investigated by Pedreschi *et al* (2004) and Mestdagh *et al* (2008) but for long residence times (in excess of three times the industrial scale values). Clearly increasing residence times would offer benefit but this paper describes an industrial study and therefore operating unit replacement and redesign is not easily achievable or financially justified. Furthermore, detailed analysis of individual crisp impact and details of within crisp variation is not considered in the paper as the scale of scrutiny is limited to a retail size packet of crisps.

The industrial manufacturing process begins with a fixed rate of 3 tonnes/hr of potatoes being washed with ambient temperature water and foreign matter removed, they are then peeled and sliced whilst being flooded with water prior to entering a cold-wash. Both the cold-wash and the hot-wash are well mixed systems. The cold-wash water is supplied at 2-3 m^3/hr and exits for processing to harvest starch. The slices then enter the hot-wash unit with variable temperature and overflow rate set by the operators. The water overflow rate is set in the range 1-5 m^3/hr based on the removal need perceptions of the operators. While the residence time of potatoes in the wash units is fixed by the line speed, the wash water flowrate variation means that the water residence time varies. The aim is to remove the maximum sugar possible by maintaining a high difference between potato and water sugar content while also being considerate to wash water costs. Both the cold-wash and hot-wash units are 2.5 m^3 rotating drums. The slices are sprayed with water on the conveyors between these washes. The slices are then dried with air blowers to reduce surface moisture before frying.

Prior studies (Ledbetter *et al*, 2020) considered the overall line behaviour and the ability to explain the acrylamide variations occurring from line settings.

Previous work has shown that at the laboratory scale reductions in acrylamide levels can be achieved through changes in processing parameters such as frying time and temperature (Williams, 2005; Martinez *et al*, 2019), slice thickness (Martinez *et al*, 2019), and slice washing temperatures (Mestdagh *et al*, 2008; Zhang *et al*, 2018). In general, it is important to decrease the reducing sugars to a level As Low As Reasonable Achievable (ALARA) before frying. Therefore, to minimise reducing sugar content pre-frying, modest changes in the processing line can be applied, such as modifying hot-wash temperature, adjusting the vessel overflow rate and with some process modifications the residence time, and these are the focus of this work. The existing control strategy involved a 'traffic light' system to classify potatoes based on sugar content. This grouped potatoes within these boundaries: green (glucose plus fructose < 7.3 mg/L), amber (glucose plus fructose between 7.3 – 44.3 mg/L) and red (glucose plus fructose > 44.3 mg/L). This is used to inform operator actions on the production line. To move towards optimised sugar removal based on scientific evidence, the effectiveness of the cold-wash and hot-wash units must be understood. This is the aim of this paper. Given the industrial nature of the processing and potential impact on product, tests need to be firstly undertaken at the pilot plant scale to determine a potential strategy and subsequently verified on the production lines.

2. Materials and Methods

2.1 Raw Material

It is important to understand the variability in the raw material. Sources of variability arise from the use of distinct varieties (*Lady Rosetta, Lady Claire, Taurus, Lady Valora*) and the inherent natural variation occurring within each variety. With particular reference to acrylamide potential, this study focuses on sugar content and variety. Currently, potato loads of total reducing sugars > 60 mg/L are considered a high acrylamide risk on the manufacturing line. A range of raw potato reducing sugar content was analysed, including > 60 mg/L threshold to assess the validity of this risk boundary.

Different process conditions are employed for each ‘traffic light’ rating, including temperature (50-80^{o}C) and hot-wash overflow rate (1-5 m^{3}/hr). The lower range is selected for ‘green’ loads, maximum temperature and overflow rates are employed for ‘red’ loads and a middle range is selected for ‘amber’ loads.

In the pilot plant studies, the commercial variety *Taurus* was utilised. During production trials all the main varieties (*Taurus, Lady Rosetta, Lady Claire and Lady Valora*) were considered and the extent of usage is summarised in Table 1

Table 1 – Potato variety and usage in manufacturing

Variety	Intake	Comment on usage
Taurus	52%	16% red or amber
Trial varieties	16%	
Lady Valora	9%	Usage is being reduced
Lady Claire	23%	Low sugar (94% green, 0% red)

2.2 Precursors Analysis

In the current established procedures, potatoes are delivered in 27.5 tonne loads and a 5 kg sample is washed and blended for analysis to determine the initial sugar content and subsequent process settings to address reducing sugar content variation. It is essential to understand the variability in observed results as a consequence of the sampling of the load and the variation in the measurements themselves. Glucose, fructose, sucrose and asparagine were measured using the Konelab Arena 30 biochemical analyser (Thermo Fisher, Courtaboeuf, France). The Konelab Arena 30 combines the addition of reagents and infrared light to determine the concentration of individual substances. Standards of D-fructose, D-glucose, sucrose (Total glucose) and L-asparagine/L-aspartic acid were purchased from Thermo-Scientific.

2.3 Variability Study

Konelab accuracy was analysed by processing five samples of the same stabilised solution (Ledbetter et al, 2020). This experiment was independently repeated four times using potatoes of varying sugar content. Results are displayed in Table 2 and show that the machine is capable of giving accurate precursor measurements.

Table 2 - Konelab accuracy

Precursor	**Standard deviation**
Fructose	± 0%
Asparagine	± 1.29%
Glucose	± 1.26%
Sucrose	± 0.15%

Multiple samples of the same load were analysed to show precursor variability. Glucose and fructose showed variability of up to 3% for ‘Green’ loads. For ‘Amber’ and ‘Red’ loads, the variability was up to 15% and 10% for glucose and fructose respectively. Asparagine and sucrose gave a maximum variability of 7% and 4% irrespective of the initial content. These percentage variations represent the extent of variation around the mean value so for example 10% variability is ±5% around the mean. Overall the measurements indicate that there is a statistical meaningful variation across a single load. It is also important to take this into account when specifying washing procedures discussed below. These are based on one measurement per load and therefore, when operating near ‘traffic light’ boundaries, knowledge of underlying, within load variation is important.

Loads are stored in a carefully controlled environment and typically processed within 24 hours of arrival. Experiments were conducted to determine potential change in precursor concentration if the load was held for 24 hours. The results showed an increase of 12% which is significant and a clear driver to adhere to the process within 24 hours policy.

2.4 Sample Handling

The data above indicate that after initial sampling, the reducing sugar content can potentially change if no further processing or stabilisation is carried out. This possibility was therefore investigated. An average pilot plant trial required fifteen samples within an hour, giving four minutes to prepare and stabilise each sample, whilst also continuing the trial. Analysing fresh samples was therefore not feasible and would risk the validity of the trial. Consequently, freezing was explored to determine whether it was an acceptable method of limiting sugar rises. Slices were taken from the process and were analysed fresh, frozen, analysed after one hour and after five days. This experiment was repeated three times to determine the accuracy of the results. Samples frozen for one hour gave a 10% increase over fresh samples and samples frozen for five days gave a 36% increase over fresh results taking 100% as the initial value. The 10% variability that came with freezing samples for one hour was considered an acceptable compromise as the variation was within the levels experienced from a fresh sample to fresh sample analysis. All samples thereafter were frozen and analysed within the same day to ensure results were not compromised and remain comparable.

The freezing procedure was optimised to reduce deviation from fresh results. Samples from the wash tanks were transferred to perforated trays and excess moisture was removed with paper towel. This was to reduce ice formation and avoid sugar dilution when blending. Slices were arranged in a single layer to the surface area for freezing and then placed in an industrial freezer at -20°C for at least one hour by which time they were frozen.

It was important to understand the maximum acceptable time before stabilising samples with Carrez solution to represent a freshly analysed value. Various samples were blended and aliquots of the pulp were stabilised at five time points across 30 minutes and analysed in the Konelab. The test was carried out four times on a range of initial sugars, whole potatoes, fresh and frozen slices. All results produced an ‘S’ curve identifying a period of time before significant sugar increase occurred. Whole potatoes and frozen slices had the longest allowable delay of fifteen minutes, fresh slices had an allowable delay of ten minutes which reduced to seven minutes for high sugar ‘Red’ potatoes. The average sample processing time before stabilising is around four minutes, confirming that sugar deterioration after sampling is not an issue providing that delay to stabilisation is minimised, which was achieved.

The above refers to the pilot plant trials which were resource limited but for the production scale trials all samples were analysed fresh due to the availability of extra resource to collect samples and transport them to the lab for analysis. When analysing raw slices fresh, the same procedure as described above was performed to prepare the samples for Konelab analysis but the slices were blended instantly with Carrez solutions to minimise time to stabilisation.

2.5 Pilot Plant

The pilot plant includes the unit operations associated with peeling, slicer, cold and hot-washing. The cold wash is a 150 L static bath of ambient temperature water and the hot-wash is a 150 L bath of water with a fixed recirculation rate. The peeler was loaded with approximately 1 kg of potatoes and peeled for thirty seconds whilst adding 500 ml of ambient temperature water to wash. The potatoes were manually sliced to a proprietary slice of varying thickness. Three 20 g samples were weighed and one sample was frozen to represent the sugar content in fresh slices. This measurement described the initial sugar concentration for all experiments due to variability in whole potatoes. The remaining two samples were added to the cold wash for a set residence time and were manually agitated to mimic the agitation experienced by the rotating drum on the production line. After cold washing a sample was frozen to capture the impact of the cold wash. The last sample was then added to the hot-wash for a set residence time at a set temperature and the hot-washed sample was frozen. Residence times of 1-5 minutes and hot-wash temperatures of 40-80°C were investigated. All potatoes were of the *Taurus* variety and ranged from 8.8-170.8 mg/L in reducing sugars before processing. While this spread may seem large, it is consistent with recent industrial raw potato analysis. To determine whether the use of fresh water was an accurate representation of the hot and cold wash waters, four samples of the hot-wash outlet water were taken from the production line. Minimal amounts of asparagine and glucose were present – a maximum of 0.3 mg/L and 23.8 mg/L respectively. Considering the production samples were taken across a period of 4.5 hours and the maximum pilot plant wash time was 3.5 minutes, it is reasonable to assume that fresh water would not cause significant deviations from production scale operation. To confirm this, a water sample of the pilot plant hot-wash was analysed after carrying out a trial on an 'amber/red' load and it showed only 0.1 mg/L of glucose.

To obtain a range of initial sugar content for pilot plant trials, batches of potatoes were held for a number of days to increase sugars. This was successful but caused an increase in potato to potato variability. As loads typically undergo processing within twenty four hours on processing-line, this could contribute to variability between pilot plant and production scale operation with potentially more in batch variability arising in the pilot plant.

3. Pilot Plant Results and Discussion

3.1 Cold Wash Operation

Firstly, it was necessary to understand the impact of the cold wash on slice sugar content. In total, 41 samples were collected from the pilot plant cold wash as shown in Figure 1.

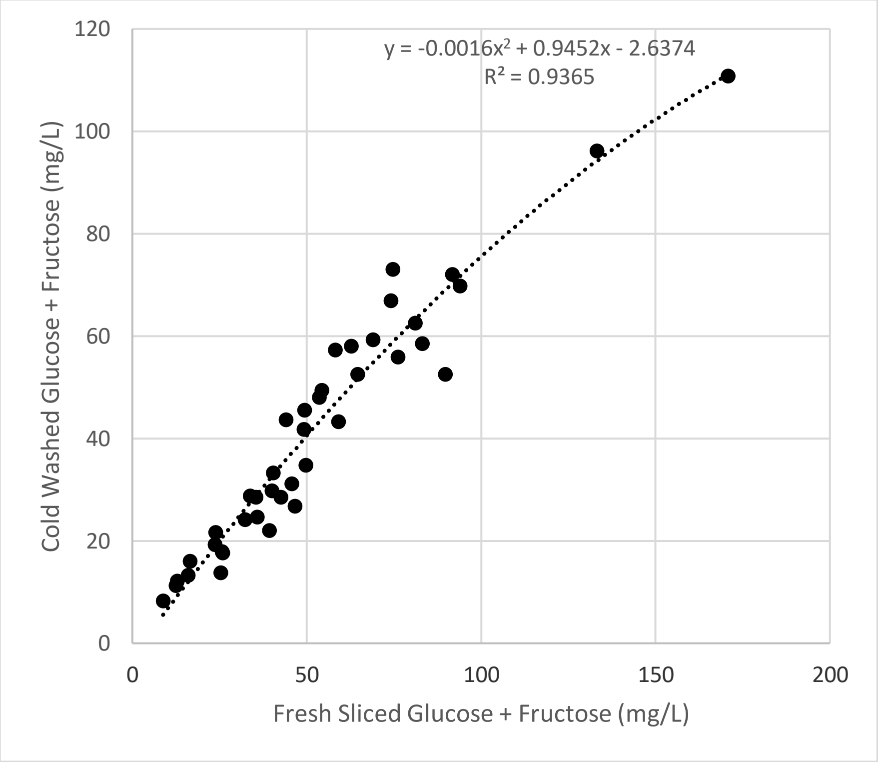

Figure 1 - Cold wash vessel sugar removal

Each sample was cold washed using water at ambient temperature for 3.5 minutes, mimicking production scale operation. A strong correlation was observed between the sugar concentration in the fresh and cold washed slices. The average reduction was calculated as 21%, which was higher than industrial expectations as the perception was that it was the hot-wash that removed significant amounts of sugar and the cold wash had limited effect. In expressing the removal percentage, 21% reduction refers to there being 79% of the sugars left compared to the inlet slices. This approach has been adopted in subsequent results that refer to removal percentages below where the 100% figure refers to the inlet concentration to that unit.

3.2 Residence Time in the hot-wash

With increased understanding of the cold wash, attention focused on the hot-wash. In the first trial, the wash temperature was set to 70^{o}C as it was proven to reduce sugar concentration in the production plant and in preliminary experimental configuration trials. The fresh slice sugar content was variable, ranging from 31-93 mg/L. Results were normalised to give percentage reduction in the hot-wash and a strong relationship was obtained, suggesting that initial sugar variation has not affected validity.

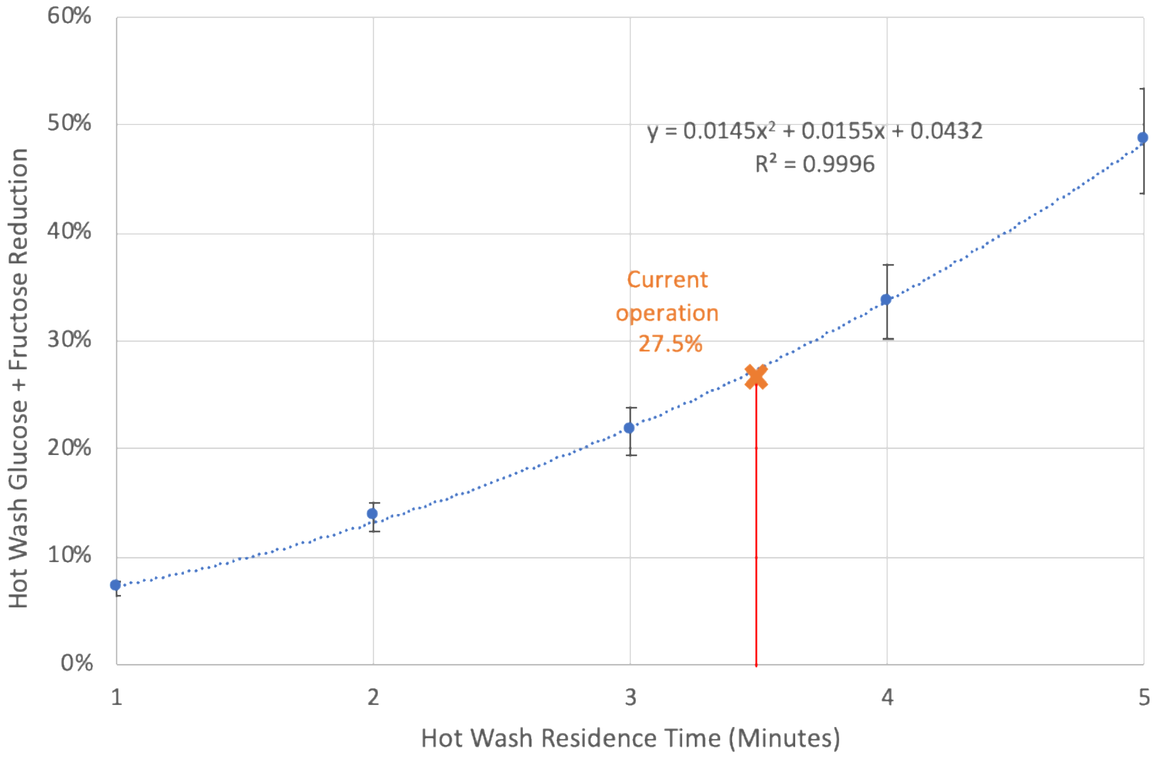

Figure 2 - Hot-wash percentage sugar reduction vs residence time at 70 °C

As seen in Figure 2, the operational residence time is 3.5 minutes, giving a 27.5% sugar reduction at 70°C. While hot-wash residence time cannot be varied over the range of one to five minutes on the industrial plant, this information provides useful indications for subsequent design modifications. The implications of the reducing sugar decrease on acrylamide potential are discussed further in section 3.3 following consideration of a broader range of hot-wash temperatures.

3.3 Hot-wash Temperature

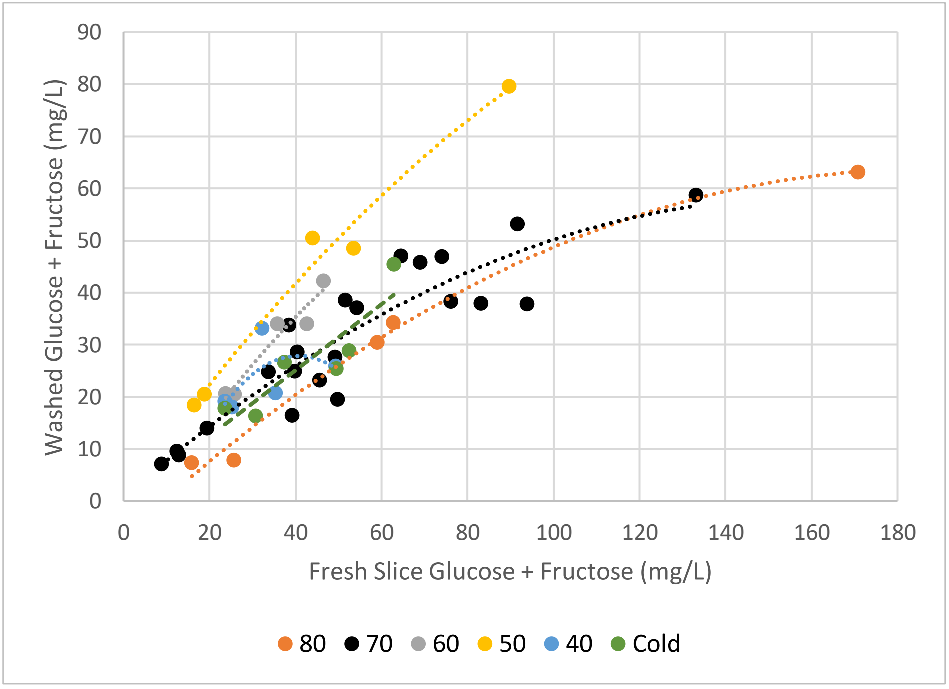

Figure 3 - Fresh slice sugars vs hot-washed sugars for a range of temperatures (15-80^{o}C) for 3.5 minutes

Figure 3 shows the relationship between reducing sugar content in fresh slices of cultivar *Taurus* compared to hot-washed slices for a range of temperatures where cold refers to ambient temperature. All slices were first cold washed for 3.5 minutes before this trial. In total, twenty two sets of samples were processed in the pilot plant for a range of initial sugars at 70^{o}C to determine the relationship between inlet and washed slices. Once this correlation was established, five sets of samples were processed for other temperatures in the range ambient to 80^{o}C to investigate the relative removal sugars compared to 70^{o}C. The assumption on the manufacturing line had been that higher temperature provides more sugar extraction. The data shows this is true for 70-80^{o}C as it is clear in results that higher temperatures will produce lower sugar content after hot-washing. However, the 40^{o}C trials showed different behaviour and were unpredictable, sometimes performing as well as 80^{o}C trials and other times performing as poorly as 50^{o}C trials.

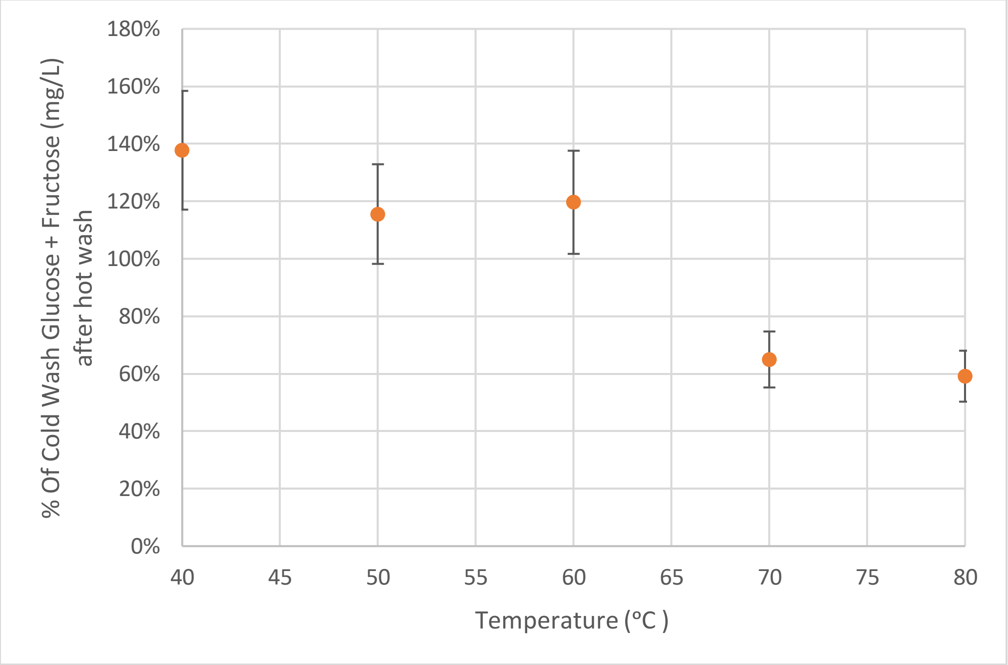

Figure 4 - Example of a pilot plant temperature trial, hot wash sugar difference as a percentage of cold washed sugars

Interestingly at the temperatures of 40-60°C an increase in sugar content compared to the inlet slice concentration was observed. Figure 4 shows averaged results from a trial where this effect occurred on all three temperatures (40, 50 and 60°C), presented in percentage sugar in blanched slices compared to the cold washed which is the 100% value, normalised to account for varying initial sugars and averaged for the five trials. The 40°C tests showed the effect in three of five trials, 50°C gave this effect for all trials and 60°C tests showed the effect in four of five trials. This suggests that in the region 40–60°C hot-washing has the impact of increasing rather than decreasing potato reducing sugar content. Unfortunately, this range is used as standard practice for ‘green’ loads. These findings are contrary to that of Raul (1984) where a strong, positive correlation between temperature and glucose removal was observed. This could be due to a longer residence time of twenty minutes employed by Raul (1984), which is unachievable on the manufacturing line without major process changes.

The observed increase in sugar at temperatures 40-60°C, can be explained by the enzyme Invertase, which converts sucrose to glucose and fructose, maximum activity is obtained between 10-50°C with a steady reduction at increased temperatures beyond that (Shankar 2014). Invertase is known for causing ‘cold sweetening’ in potatoes where they are stored in colder conditions, causing sugar increase (Pressey, 1966). Chibbar (2016) describes two types of Invertase, an acidic and an alkali version. The optimum pH for the alkali version is 7.5, which is what the hot-wash currently operates at. Enzyme Educational Institute (2019) state that Invertase is active up to 60°C, which agrees with findings in this study as the effect has not been observed beyond this temperature.

Increase in sugars from 40-60°C confirm that the combined cold / hot-wash mode of operation is counterproductive in sugar removal effectiveness and also a significant waste of energy. Constantly running the hot-wash at 70-80°C is undesired because 'green' loads could theoretically result in low acrylamide without hot-wash treatment. As it is impractical to bypass the hot-wash for certain loads at production scale, 'double cold washing' was trialled in the pilot plant where cold wash residence time was doubled to seven minutes, replicating the production process if all heat sources to the hot-wash had been removed. This experiment was repeated six times and showed to give significant sugar removal in all pilot plant trials. For loads with initial reducing sugars concentrations < 47 mg/L, double cold washing is equivalent to blanching at 70°C (Figure 4) for sugar reduction. These findings could result in major energy savings and challenges the current 'red', 'amber', 'green' system adopted to guide operational staff. Instead of categorising potatoes into three categories, it could be beneficial to have only two. Before such a modification can be made it is necessary to confirm the behaviour observed in the pilot plant occurs at production scale as discussed below.

Given that the overall objective of sugar reduction is to reduce acrylamide, it is desirable to equate sugar reductions achieved to likely potential acrylamide reduction when assessing wash performance.

As frying was not carried out for pilot plant trials, an acrylamide prediction was required. Previous work by Ledbetter *et al* (2020) produced acrylamide prediction from historic production line data using fructose, glucose, sucrose and asparagine values as well as fryer temperature. The fryer temperature was set to idealised conditions (a constant) in the estimates that follow. The predictor output is a probability between 0 and 1 that identifies the likelihood of high acrylamide potential, based on the benchmark level of 750 ppb. Allowing for the variations in the ratio of reducing sugar concentration, it is likely that if the combined reducing sugars are below 43 mg/L it would lead to acrylamide lower than the benchmark threshold as predicted by the model output. Considering the information in Figure 3, a double cold wash is suitable for this concentration and is until 47 mg/L above which hot-washing at 70°C is preferable. The 47 mg/L limit is set as in Figure 3 as this is where the double cold wash and 70°C wash deviate from each other. This binary system (longer) double cold-wash / hot-wash could be beneficial in standardising the operator's decision-making process, leaving less room for interpretation.

3.4 Energy Usage

There is a large potential energy saving with double cold washing all loads with initial reducing sugars <47 mg/L. Analysis was performed on energy usage from 2018 to determine costs saved if double cold washing was implemented. Weighted factors were applied to account for higher sugar loads running at higher temperature and overflow rate. Natural gas is used to produce steam that heats hot-wash water. In 2018, loads under 47 mg/L made up 93% of the total intake at the industrial facility, if they were double cold washed, natural gas usage could be reduced by 85%, saving an estimated £167,000 per year. To substantiate these calculations, the data from the pilot plant study observed for the variety *Taurus* where confirmed for all major crisp varieties on the production plant.

3.5 Confirmatory questions to consider for the production plant

The pilot plant results, if replicated at the production scale (and transferable between potato varieties), could lead to a change in operational procedures on the production line but confirmation of comparable behaviour needs to be demonstrated. Four initial questions arising are:

- Are the sugar removal efficiencies comparable between pilot and production plant?
- Does mid-temperature washing increase reducing sugar content at the production scale?
- Is double cold-washing as effective for all but extreme 'Red' loads?
- Does wash water contain low levels of reducing sugars so as to maintain concentration gradient?

Going beyond the pilot plant findings, additional considerations for the production scale trial are:

- Is the behaviour observed for *Taurus* seen for other varieties?
- Does double cold-washing cause texture concerns?
- Does the consumer identify a change in experience?
- Are reductions observed in the levels of acrylamide concentration?

4. Production Scale Results and Discussion

To answer these questions a series of production scale trials were undertaken followed by a longer period of operation of the double cold washing strategy. Firstly, four production scale trials were carried out for which standard operating conditions were compared to double cold-washing in order to investigate scaling the process from the pilot plant. The trials covered all main varieties of the November-July crop as described in section 2.1, including two loads of low sugar *Taurus*, one load of high sugar *Lady Valora* and one load of low sugar *Lady Claire*. Each trial focussed on a specific potato load to remove any variability from a load change which could result in different varieties, and included tuber count, specific gravity and sugar content being compared. A load runs on the line for approximately 8 hours depending on downtime and this allowed up to nine sets of samples to be taken for a given trial, with two to three sets of standard cold then hot-washed samples and two to six sets of 'double cold-washed' samples taken for each trial. A set of samples was analysed which included all raw samples equivalent to those taken in the pilot plant as described in section 2.5 as well as fried product samples and hot-wash water. As the hot-wash overflow rate was suspected to be a weak contributor to sugar removal, it was set at 1 m^3/hr for the duration of the trials while noting that this may be insufficient for higher sugar loads. Raw potato slices were sampled as the load ran down the line, a period of delay was implemented between samples for the residence time of the vessels, 3.5 minutes for the cold and hot-wash and five minutes for the fryer. As well as analysing sugar and asparagine content in raw slices and hot-wash water, fried product samples were taken for acrylamide and sensory analysis and process conditions were logged automatically at thirty second intervals, including hot-wash temperature and overflow rate, fryer temperature and fried product oil and moisture content.

As the double cold-wash operates under ambient temperature conditions it ranged from 18 to 20˚C throughout the trials. Table 3 shows the sugar content indicated for the load and hot-wash temperatures for each trial.

Table 3 – Production plant potato summary

Trial	Variety	Initial Sugar Content (mg/L)	Standard Hot-wash Temperature (°C)
1	*Taurus*	16.8	60
2	*Taurus*	7.5	70
3	*Lady Valora*	63	70
4	*Lady Claire*	10.5	55

Once the longer cold-wash method of operation was shown to be effective in production scale tests, more extensive trials were undertaken. At the time of sampling, the new crop, *Lady Rosetta*, had been harvested and was being processed. The opportunity was taken to determine whether longer cold-washing was suitable for this variety also. Five sets of samples were obtained for each line in the longer cold-wash condition only.

The results from the production scale trials allowed the answers raised by the pilot plant results to be addressed.

Are the sugar removal efficiencies comparable between pilot and production plant?

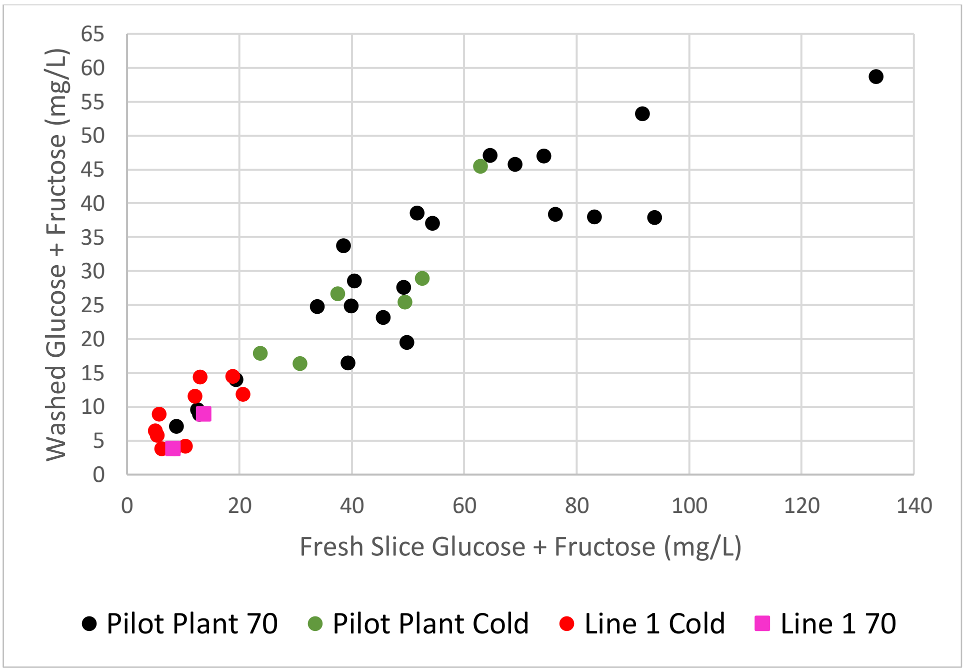

Figure 5 – Comparison of pilot and production scale for sugar removal efficiency

Figure 5 shows fresh slice combined glucose + fructose content vs hot-washed glucose + fructose content, representing the whole washing process for both pilot plant and production process line 1 70^{o}C operation vs double/longer cold washing. As the pilot plant trials focussed only on the *Taurus* variety, this is the only variety shown (production trials 1 & 2). It is clear that the production scale data is consistent with pilot plant results, although the sugar ranges observed are narrower in production. To determine this effectiveness it was necessary to determine removal compared to sugar present in potatoes leaving the cold wash. The mean sugar reduction in potatoes leaving the second cold wash was 12% compared to the first cold wash exit (noting that this is for low sugar load potatoes). This study shows that for up to 20.5 mg/L initial combined glucose and fructose (the highest concentration for trial 1 & 2), double cold washing is suitable for production lines in terms of sugar removal efficiency and verifies the behaviour observed in the pilot plant. This threshold accounts for 78.7% of loads from the 2018/2019 intake that could have been double cold washed.

These results gave confidence that the double cold wash approach was effective so a longer trial was undertaken featuring *Lady Valora* and *Lady Rosetta* varieties as discussed below.

Does mid-temperature washing increase reducing sugar content at the production scale?

Considering whether increases in sugar concentration were observed for washing at lower than 70^{o}C, the *Taurus* production plant trial at 60^{o}C resulted in a sugar increase in potatoes leaving the hot-wash of around 30% which is comparable with pilot plant results. Trial 4 subsequently considered a hot-wash at 55^{o}C for the *Lady Claire* variety only and a 23% increase in sugar was observed for potatoes leaving the hot-wash, which is again comparable with *Taurus* data and suggests that this observation is not variety specific. The prime purpose of the production trials was to demonstrate double cold-wash effectiveness, so the number of trials demonstrating the problems of cold / hot-wash were limited but sufficient to demonstrate comparability with pilot plant.

Does wash water contain low levels of reducing sugars so as to maintain a concentration gradient?

The effective removal of sugar from the potato slices relies on the maintenance of a concentration gradient between the higher concentration in the potato slices and the lower concentration in the wash water as the driving force for mass transfer. While the pilot plant adopted a high water to potato ratio to ensure that the driving force was at its maximum, in production the water and energy efficiency is a critical consideration along with the reduction of sugars. The production plant trials used the minimum water flowrate of $1m^3$/hr and the concentration of sugars in the second cold wash was monitored. For trials with the low sugar loads, the sugar concentration in the wash water was 1 mg/L or lower compared to sugar concentrations in the potatoes which ranged from 10 to 20 mg/L, hence establishing an effective driving force. The more concerning result arose for the higher sugar load samples which can be seen in Figure 6. Here, the initial hot-wash phase switches to double cold washing and an increase in wash concentration to 15 mg/L. It only falls again towards the end of the test when a line stop occurs at 12.30 pm but the flushing of the wash tank continues, hence the reduction in concentration.

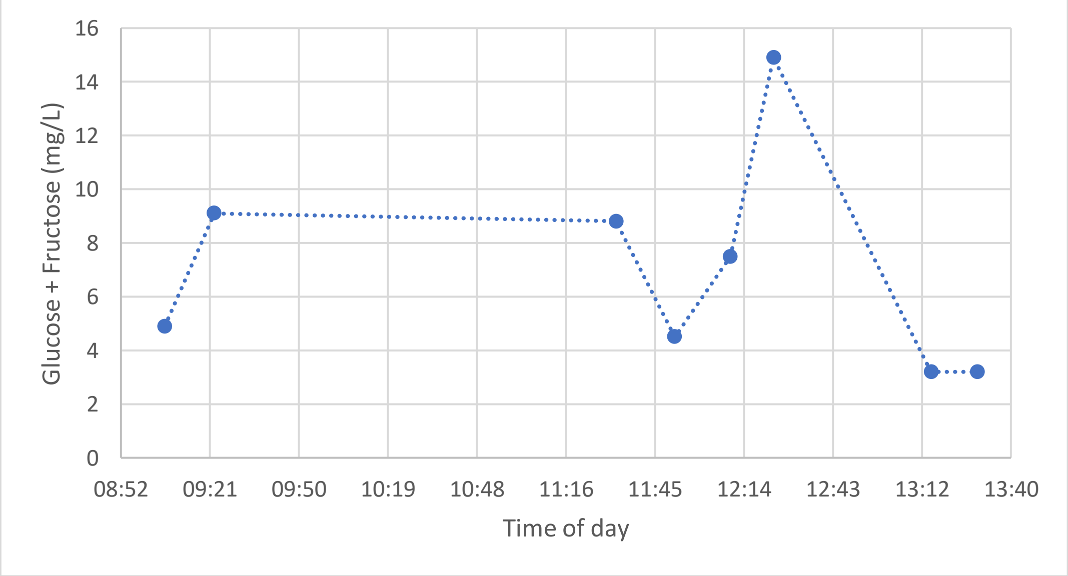

Figure 6 – Wash tank sugar concentration for high sugar concentration potatoes and low water flow

A rise to 15 mg/L represents a decrease in mass transfer driving force of 25% and since residence time is fixed, effectively a reduction in efficiency of sugar removal of around 25% occurs. The primary objective is to maximise sugar removal to minimise the propensity to produce acrylamide and hence any sugar increase in the wash water is problematic. Thus, for lower sugar loads a water flowrate of 1m^3/hr is sufficient and in the case of high sugar loads it is necessary to operate the wash tank at a flowrate of 3 m^3/hr. Prior to this study the operators had the ability to increase this to 5 m^3/hr but the wash water concentration did not require this and resulted in unnecessarily high water usage, along with the energy to heat that water to 70°C.

Is the behaviour observed for *Taurus* seen for other varieties?

Figure 7 shows initial glucose + fructose vs post washed glucose + fructose readings of potato slices, describing the whole washing process per potato variety. The *Taurus* data set includes all 70°˚C hot-washed, double cold-washed on-line and pilot plant data. Other varieties include 70 °C hot-washed and double cold-washed production data. The exception to this is *Lady Claire*, which were washed at 55°C. It is clear that lower sugar *Taurus*, *Lady Rosetta* and *Lady Claire* experience similar sugar removal regardless of whether 70°C hot-wash or double cold wash operation is utilised, as there are no clear outliers within the data set. However, *Lady Valora* has shown a clear difference to the other varieties with a lot more variability, especially in the double cold wash condition. It is assumed that at low sugar levels *Lady Valora* will be suitable for double cold washing, but since this variety has the highest average sugar content, this study further justifies reduced usage of this variety. This will lower the demand for hot-washing and therefore result in energy savings.

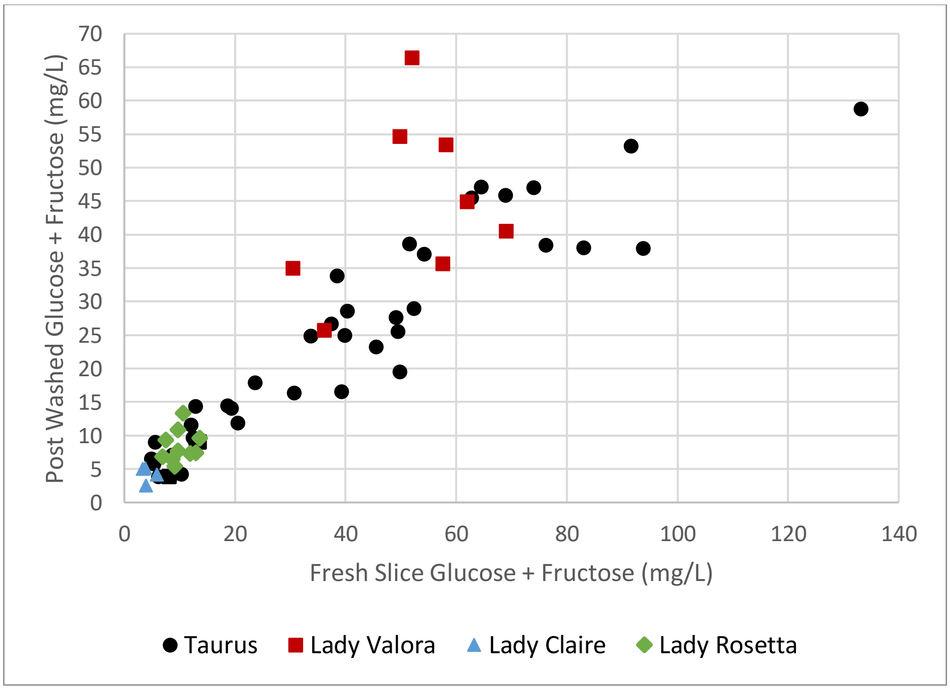

Figure 7 – Comparison of pre and post washing at pilot and production scale by variety

Are reductions observed in the levels of acrylamide concentration?

Fried product samples were obtained from the fryer exit inspection belt and were sent for acrylamide analysis. The results, however, contain a lot of variability due to the instability of the fryers, particularly around line start-up and shutdowns. Acrylamide formation increases exponentially above 154 °C (Knol *et.al.*, 2005), and this is a regular occurrence during start up/shut downs as well as when there are fluctuations in feed of raw slices to the fryer. This extra source of variability needs to be taken into account when observing results with means to determine the effects of double cold washing. Acrylamide results were considered final confirmation towards whether double cold washing was suitable for permanent implementation in that the method could produce fried product that contained less than 750 ppb acrylamide. Double cold washing was functional on all process lines for a trial period of 3 weeks, with routine acrylamide samples being taken. In total, 2 weeks of acrylamide results on the new crop (*Lady Rosetta*) were compared to the same weeks in 2018 for all process lines. It was found that 2019 values were slightly lower in acrylamide (445 ppb average compared to 456 ppb average in 2018) and sugar content of potatoes is slightly higher in 2019 (15.9 mg/L average compared to 13.8 mg/L average in 2018), both of these factors suggest that sugar is being removed more efficiently than in 2018, when the hot-wash was operating from 55-80°C. However, it is clear that the largest contributor to higher acrylamide is the frying process, which is why there are no major improvements seen in the results. However, it is still beneficial to have a small change in acrylamide as double cold washing comes with additional benefits of energy, water and oil savings.

Does double cold-washing cause texture concerns and impact customer experience?

Samples from each trial were sent for sensory analysis in which triangle tests and comparative profiles were carried out. Both flavoured and un-flavoured samples were analysed for appearance, aroma, texture and flavour differences. All flavoured samples passed the triangle test, confirming that there was no significant difference detected at a 95% confidence level. This means that double cold-washing has not changed the product enough that a consumer could detect a difference in the final product. The process of starch gelatinisation is not severe enough to show a change in sensory results, between double cold washing and 70°C hot washing.

5. Conclusion

This study set out to investigate the wash regime utilised within a crisp manufacturing factory and the underpin the operations with scientific justification. Prior to the study, a three-level approach based on high, medium and low sugar levels was adopted. The approach adjusted hot wash temperature and water flowrate for each level. Importantly, for the medium level, conditions were selected by individual operators based on experience. With the perception that lower sugar levels required less removal, so lower temperatures could be used to reduce energy consumption and lower water flowrates to reduce water usage. The outcome of this study has led to the adoption of a new two-level strategy which is more energy efficient, cheaper, does not impact on consumer experience and has the potential to reduce acrylamide levels. The key findings resulted in changes to the residence time and temperature of the hot-wash.

Sugar removal from the cold-wash was more effective than expected (21% reduction, highly dependent on initial sugar concentration), leading to a “double cold-wash” for loads with sugars <45 mg/L with the lowest water flowrate. Additionally, it was found that a hot-wash temperature of 40-60°C was counterproductive, increasing sugar content and therefore the potential for acrylamide formation. For higher sugar loads, a 70°C hot-wash with medium water flowrate is sufficient to avoid sugar build up in the wash water and for sugar removal from the potato slice.

Based on 2018/2019 season, 97% of the loads sugar content was <45mg/L, implementing the above two-level scheme, offers major energy savings, natural gas usage could be reduced by 85%, saving £167,000 per annuum for a single production line. Critically, a sensory panel could not detect differences between the original product and the double cold-wash product.

The study has considered crisps at a scale of scrutiny of a retail size packet as that is what the customer experiences. This study did not focus on the behaviour experienced at the crisp or within crisp scale but the findings of this study indicate that deeper understanding at this scale would be beneficial from a fundamental science perspective.

Ultimately this work has delivered two major industrial findings:

- Double cold-washing is as effective in sugar removal as cold-washing followed by hot-washing
- The additional benefit of this is a reduction in energy and water use with associated cost savings

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