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Optimizing thermal product processing in oat drink production

Milk alternatives such as soy, almond, and oat drinks have become staples in supermarkets due to their health benefits, great taste and sustainability affects. An increasing number of breweries are entering oat drink production, as the manufacturing process closely resembles traditional brewing. This allows efficient repurposing of existing equipment such as mills, mash tuns, and storage tanks. For industrial-scale production, thermal preservation by direct heating is the preferred method to ensure microbiological stability while maintaining desirable sensory qualities and minimizing off-flavours. A key factor for cost-effective production is maximizing the operational time of the ultra-high temperature (UHT) process, minimizing interruptions for cleaning and sterilization. However, the formation of fouling layers in the high-temperature sections of the system – often within just a few hours – poses a significant limitation. The extent of fouling is strongly influenced by the upstream hydrolysis process. This study aimed to investigate the factors contributing to fouling to enable precise adjustments to equipment and process parameters, as well as to optimize cleaning procedures (CIP). Therefore, oat drink was produced in-house from oat flour via enzymatic hydrolysis and subsequently subjected to direct thermal treatment at both pilot and industrial scales. The results demonstrated a clear influence of the applied temperature profile on fouling behaviour. Sedimentation characteristics, colour development, and sensory attributes of the thermally treated oat drink were evaluated.

Descriptors: oat milk, oat drink, brewhouse, mashing, UHT, denaturation, fouling, plant based, plant proteins, flavour

1 Introduction

The global market for plant-based beverages has demonstrated robust growth in recent years, accompanied by a notable expansion in the variety and availability of products across retail environments. While the consumption of cow's milk is either stagnating or experiencing a slight decline globally, the demand for plant-based drink alternatives – particularly oat-based drinks – is projected to grow substantially through 2029 (fig. 1, 2). [8]

The considerable variability in raw materials such as oats, peas, lupins, and almonds introduces a wide range of compositional differences into the production process. These variations can significantly alter both the processing parameters and the fouling behaviour during thermal treatment.

Fouling in the beverage industry is a phenomenon that has been very well researched for the beverage, brewery and dairy industry [1, 2]. Exact denaturation temperatures for flocculating individual proteins, minerals or fats to be expected are known and are used to relieve the critical high-heat sectors for an indirect heat transfer. Also, in the brewery industry a specific denaturation for specific proteins is an important process – for example to create a good haze stability in wheat beer [11, 12].

The use of direct steam injection or infusion processes (DSI) is often the best choice when it comes to producing high-quality products with maximum run time for all production machinery. All this experience and analytical processing are missing for plant-based beverages – especially oat drink.

Oat drink can be produced by two methods. The first utilizes a pre-processed, viscous oat syrup that is diluted with water and blended with ingredients such as salt and oil. This method is not scope of this study.

The second involves enzymatic hydrolysis of oat grains or flour in water followed by enzyme deactivation and separation. According to Hinrichs et al. [6], a representative production process for oat - based beverages using enzymatic hydrolysis is illustrated in figure 3.

The key step of oat drink production – the enzymatic hydrolysis – is started by adding enzymes to the oat flour-water-mixture. The aim of hydrolysis is converting the existing starch into smaller molecules. The hydrolysis is divided into two parts: gelatinisation and saccharification and has impact on oat drink´s taste, sweetness and yield.

After successful hydrolysis the added enzymes need to be inactivated. This step is essential for preventing the development of

https://doi.org/10.23763/BrSc25-08feilner

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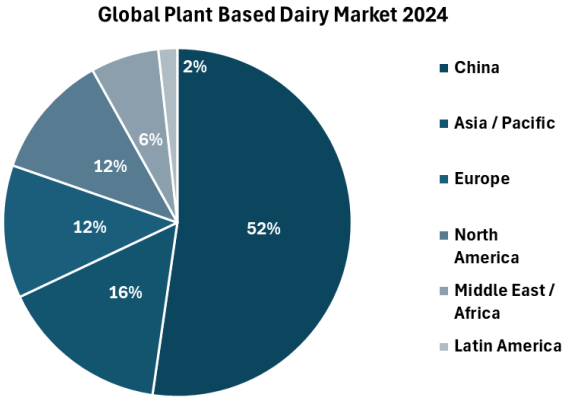


Fig. 1 **Global plant based dairy market 2024 [8]**

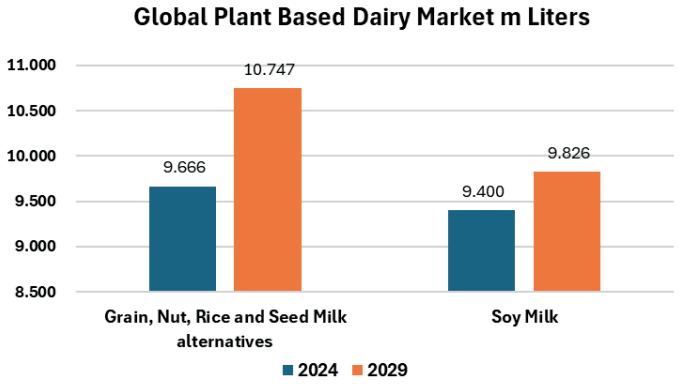


Fig. 2 **Global shared plant-based market 2024 vs. 2029 in M Liters [8]**

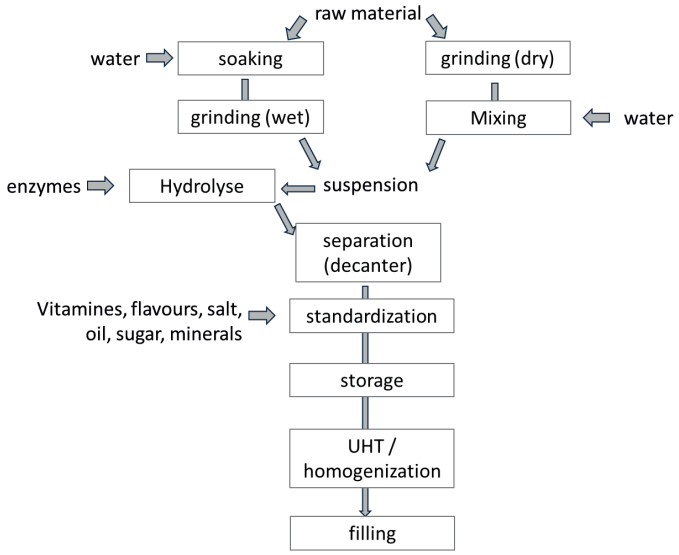


Fig. 3 **Schematic production process for oat-based beverages [6]**

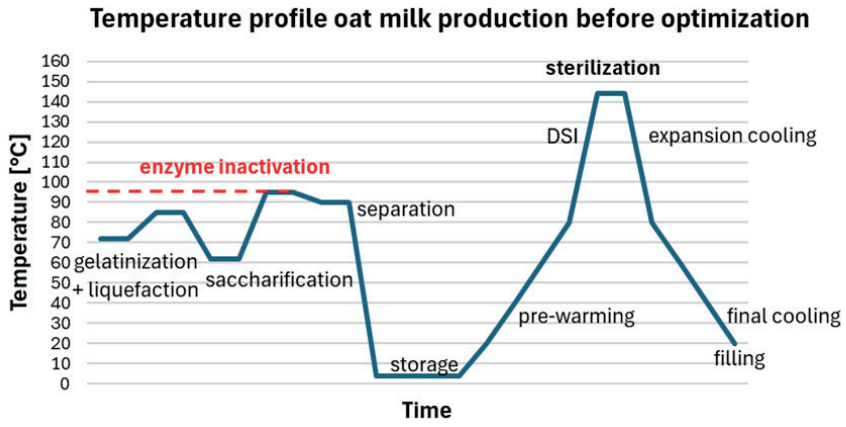


Fig. 4 **Temperature profile production process with a standard enzyme inactivation temperature [3]**

unwanted off-flavours during the oat drink´s shelf life [3]. The solids are separated from the plant dispersion. [6]

The resulting oat base concentrate is then mixed with water, salt, and oil to the formulated beverage. To ensure shelf stability at ambient temperature for several months, the oat drink undergoes ultra-high temperature (UHT) treatment. Following aseptic homogenization, the oat drink becomes commercially sterile and ready for distribution and consumption. [6]

Figure 4 illustrates a representative temperature profile for oat drink production, based on developments by Krones AG. Depending on the optimum temperature of the selected enzymes, enzymatic hydrolysis (gelatinisation and saccharification) takes place between 60 °C and 85 °C. The enzymes are thermally inactivated at a temperature of at least 95 °C at the end of hydrolysis. [3]

The solid components present in the plant-based dispersion are separated using a decanter centrifuge. This step is carried out at 90 °C. Following standardization, the resulting raw drink is stored at 4 °C.

To ensure the microbiological shelf life of the final drink for several months, the raw drink undergoes ultra-high temperature (UHT) treatment. For this purpose, the product is heated to 135 – 150 °C for a few seconds, either by direct steam injection or infusion, or via tubular heat exchangers.

After thermal treatment, the oat drink is cooled to 80 °C and subsequently subjected to aseptic homogenization.

The drink is then cooled to the filling temperature and stored in a sterile tank until the filling process begins.

Following thermal processing, the entire system must be maintained under aseptic conditions to prevent microbial recontamination.

In previous industrial oat drink production runs that followed the temperature profile shown in figure 4, severe fouling was observed in the thermal sterilization section (see fig. 5).

A limiting factor in the UHT process is steam consumption, which is, among other parameters, constrained by the degree of opening of the steam control valve. The valve opening level thus serves as

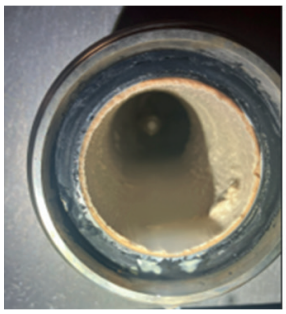


Fig. 5 **Initial situation: strong fouling in the UHT with pre-treatment at only 95 °C**

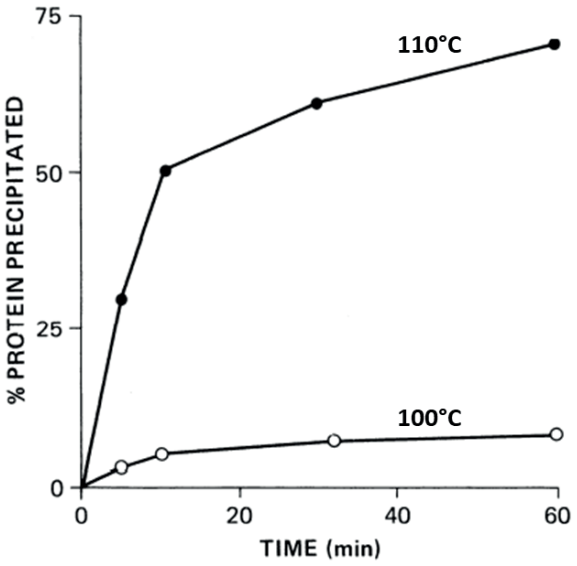


Fig. 6 **Effect of temperature on the rate of heat coagulation of oat globulin at 100 °C and 110 °C [4]**

an indirect indicator of fouling within the system. Once the valve reaches its maximum position, continued operation is no longer feasible, and the system must be shut down for cleaning. Therefore, maintaining a stable or only minimally increasing control valve level over the course of production is a critical objective.

Another important aspect concerns the fouling of temperature sensors. Excessive fouling can thermally insulate the sensor elements, leading to inaccurate readings and, ultimately, a loss of effective temperature control.

It is hypothesized that, in addition to temperature-dependent enzyme inactivation, other endogenous proteins present in the oat drink may also undergo structural denaturation because of thermal processing.

The study by Ma et al., and Rohde et al. [4, 5] provides an initial indication of the temperatures at which the relevant oat proteins begin to denature. The indication is that the predominant protein fraction in oats – globulins – begins to denature at temperatures around 100 °C. A increase in the degree of denaturation is observed at 110 °C, indicating a temperature dependent structural transition of these proteins during thermal processing (fig. 6).

Based on the findings of Ma et al. and Rohde et al. [4, 5], it is hypothesized that increasing the temperature of the enzyme inactivation step from 95 °C to 100 °C or 110 °C may lead to a reduction in fouling within the thermal sterilization section of the process.

The resulting enhanced denaturation of globulins at 110 °C promotes the formation of protein agglomerates, which are subsequently removed during the following separation step. Therefore, these denatured protein structures are no longer available in downstream processing stages, thereby reducing their contribution to fouling formation.

Besides an economical UHT process, the impact on product quality in terms of physical and biochemical stability, as well as on the aroma profile, must also be assessed.

For the flavour profile, a sensory test should be conducted regarding the relevant flavour profiles [9, 10]. Individual flavours in a direct comparison between two samples are certainly an indicator of differences. However, as in many areas of the food industry, aromas are always considered part of a composition – which can influence each other positively or negatively – and the solvent and thus the overall matrix are also crucial for the perception of the aroma.

McCarron [15] found out in a multiple factor analysis that brown bread aroma was found to be significantly positively correlated with 2-methylpropanal, 3-methylbutanal and 2-methylbutanal. All branched chain aldehydes described as having a malty and chocolate aroma [19], as well as with methyl acetate. Brown bread flavour is also significantly positively correlated with methyl acetate, 2-methylbutanal and 3-methylbutanal. 3-Methylbutanal is an amino acid-derived key flavour compound in bread, with a low taste threshold [19], which may have resulted in the brown bread aroma and flavour correlation. A nutty aroma was found to be positively correlated with heptanal, a compound typically described as having a fatty aroma when in isolation [10]. Sweet and wet oats aroma were also both found to be significantly positively correlated with heptanal yet negatively correlated with methyl 2-methylbutanoate.

Wet oats flavour was shown to be positively correlated with hexanal, which often imparts a green aroma [10], as well as with pentanol, 2-hexenal and heptanal, yet was again negatively correlated with methyl 2-methylbutanoate. Single cream flavour was significantly positively correlated with methyl propanoate and 3-methyl-2-butanone, whilst being negatively correlated with benzaldehyde, 6-methyl-5-hepten-2-one, limonene and non-anal.

Off-flavours in oat milk alternatives may result from the presence of unsaturated fatty acids and lipoxygenases that can lead to the formation of n-hexanal and n-hexanol, which are associated with a “beany” or “off” flavour [15, 16]. Production and storage can lead to lipid degradation and oxidation, causing the development of these off-notes [15, 17]. This may be problematic, as hexanal is considered a rancidity marker and may affect the acceptability for oat milks [15, 18].

For the sensory evaluation a flavour close to the taste of “popcorn” is also an established off-flavour. The popcorn flavour, represented

through DMS, Diacetyl and Acetoin, is an indicator that intensifies with the thermal stress of the product and negatively influences the taste of the product.

2 Materials and Methods

2.1 Preliminary test: Pilot plant scale

Preliminary investigations were conducted at the Steinecker AG brewing pilot plant in Freising and the Krones AG process technology center in Neutraubling.

The objective of the preliminary experiments was to experimentally determine the denaturation temperature range of the proteins present in oat-based beverages. Based on the findings of Ma et al. and Rohde et al. [4, 5], the preceding literature review suggested a denaturation range between 110 °C and 120 °C.

Initially, an oat base was produced via hydrolysis using oat flour, enzymes, and water. The detailed procedure is illustrated in figure 7. The applied approach is based on the empirical expertise of Steinecker AG bewing test center.

No additional enzyme inactivation step was performed. Following the completion of hydrolysis, the oat base was clarified at 90 °C using a decanter to remove solid particles and subsequently cooled to 6 °C.

The oat drink was formulated from the oat base, water, salt, and rapeseed oil. The final product had a total dry matter content of 9 %, with 0.1 % salt and 1.5 % oil.

To compare the effects of different heating methods (direct vs. indirect heating), the obtained oat drink was treated using both an infusion process and a tubular heat exchanger. The corresponding temperature profile is depicted in figure 4.

2.2 Main experiment: Industrial scale

The experiments of the main trial were conducted on an industrial-scale direct steam injection system „VarioAsept D". The production of oat base followed the same procedure as described in the „Preliminary Trials" section (fig. 7). Batches of up to 70,000 liters were produced in order to simulate a production time relevant to industrial practice. The process conditions were identical to those used at pilot scale (fig. 7).

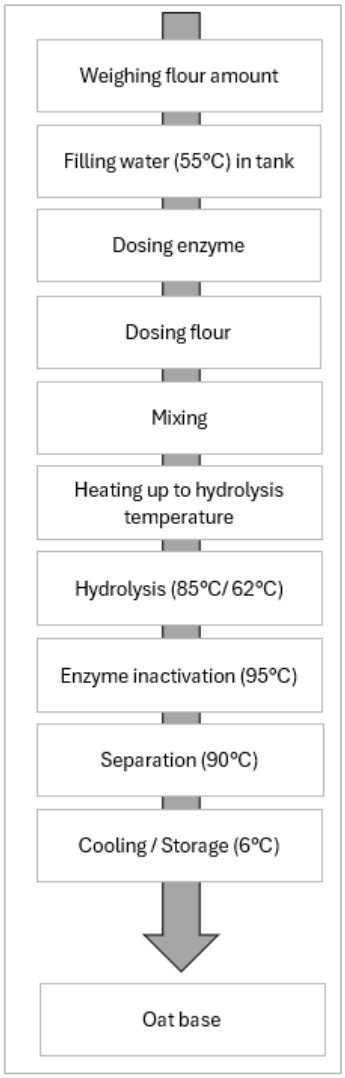


Fig. 7 Production process oat base

Identical to the pilot-scale tests, the product was preheated to 80 °C in a tubular heat exchanger. The subsequent high-temperature step was carried out using direct steam injection (DSI), rapidly heating the product to 144 °C. Immediately after this, the product was cooled down to 80 °C through an expansion process, during which the concentration was restored to its pre-DSI level. Final cooling to the filling temperature (< 20 °C) was achieved using a tubular heat exchanger, which was recuperatively connected to the preheating unit.

In the initial phase of the investigations, enzyme inactivation was carried out at 95 °C. In the further course of the study, the inactivation temperature was increased to 100 °C and later to 110 °C.

To evaluate the influence of increased enzyme inactivation temperature on protein denaturation and the associated fouling behaviour within the thermal processing system, the following parameters were monitored and qualitatively assessed:

- Degree of opening of the steam control valve in the high-temperature heater during continuous operation;
- Fouling formation observed on the sight glass located downstream to the heater;
- Duration of production without the need for intermediate cleaning or CIP.

The opening degree of the steam control valve provides a direct indication of the amount of steam required to heat the oat drink to the target temperature. An increasing valve opening over time signifies a growing demand for thermal energy to maintain the desired outlet temperature. This trend is indicative of irregularities within the thermal system, most notably the formation of fouling layers.

The length of uninterrupted production time without requiring a Clean-in-Place (CIP) or intermediate cleaning procedure serves as an indirect indicator of the system's fouling behaviour. A longer production duration without cleaning interventions suggests lower fouling rates and greater process stability. Conversely, a reduction in production time before cleaning becomes necessary may indicate accelerated fouling, likely due to increased protein instability.

2.3 Physical product stability

Sedimentation tests were performed to assess the physical stability of the oat drink samples. Equal volumes of the product were transferred into transparent containers of identical dimensions. The height of the sediment layer was measured at defined time intervals. The end point of sedimentation was defined as the time at which no further increase in sediment height or change in layer thickness was observed. Even after extended periods - up to several days - no additional sediment formation occurred, indicating the completion of the sedimentation process.

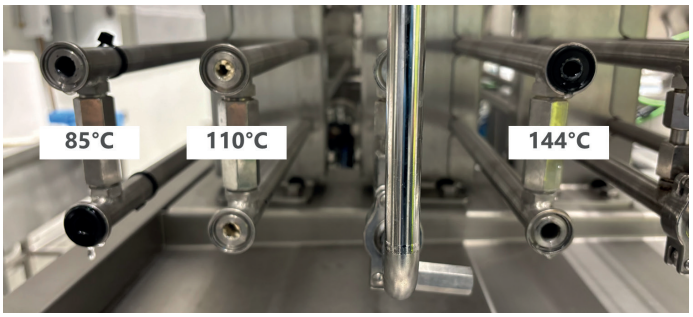


Fig. 8 **Fouling in the different sections of the tubular [7]**

2.4 Product quality and flavour profile

To gain a clearer understanding of the effects resulting from elevated temperatures applied prior to UHT treatment – intended to induce pre-denaturation – samples were analysed by the Research Center Weihenstephan for Brewing and Food Quality, Technical University of Munich.

All standard analyses were conducted in an accredited laboratory, with each measurement performed in technical duplicates. The following parameters were analysed using the corresponding validated methods:

- Colour (MEBAK Bd. WBBM 2.12.1.2012): by visual comparison using a colour comparator;
- Free DMS (WBBM 2.23.1.1 2012): by static headspace method coupled to gas chromatography with flame photometric detector (HS-GC-FPD);
- Aldehydes: in-house method as described by Lehnhardt et al [13].

Additionally, colour was determined by spectral photometry (extinction at 430 nm) in accordance with MEBAK R- 05.07.110 [2016-03] with modifications to the standard protocol, including filtration through a 0.2 µm membrane prior to measurement.

Sensory analysis was carried out by a panel of five DLG-certified tasters, each of whom undergoes regular weekly training to ensure consistency and reliability. The evaluation began with a descriptive test in accordance with DIN 10964:2014, followed by a quantitative descriptive analysis. In the latter, selected sensory attributes were rated on a scale from 0 (not perceptible) to 5 (very strong impression). Tasters first assessed the samples individually; subsequently, a consensus profile was established based on group discussion.

3 Results and discussion

3.1 Preliminary test: Pilot plant scale

The oat drink made of self-produced oat base heated using indirect heating by a tubular heat-exchanger showed a soft, beige coating in the area above 110 – 120 °C after 60 minutes production (fig. 8).

According to Ma et al. and Rohde et al. [4, 5], denaturation of globulins – the predominant protein fraction in oats – occurs more intensively at temperatures around 110 °C. This observation could be confirmed within the experimental setup. No fouling or precipitation was detected in the colder or hotter sections of the tubular heat exchanger. Fouling deposits were observed exclusively in the region where the oat drink reached temperatures between 110 °C and 120 °C.

After a 60 minutes production of oat drink using infusion technology exhibited a soft, thick layered, brown coating on the sight glass after the infusion tank (fig. 10). This area had a temperature between 143 and 144 °C.

Upon entering the top of the infusion tank, the oat drink had a temperature of 80 °C. During its descent to the bottom of the steam-filled infusion tank, it is instantaneously heated to 144 °C within a fraction of a second. This means that the denaturation temperature of globulins, approximately 110 °C, is rapidly exceeded. Since there is no contact between the oat drink and the tank surface during the fall, it is assumed that the precipitated agglomerated proteins accumulate at the first point of contact with the tank surface. This area corresponds to the narrowed outlet of the tank, which leads into the sight glass shown in figure 10. The brown discolouration of the fouling layer is attributed to the formation of melanoidins as part of a Maillard reaction.

Fig. 9 **Clean sight glass after infusion tank [7]**

Fig. 10 **Sight glass with massive fouling layer [7]**

Based on the results of preliminary trials on a pilot scale, it was concluded that the protein fractions present in oats predominantly denature at a temperature of around 110 °C. The resulting protein agglomerates precipitate, leading to fouling formation within this temperature range.

3.2 Main experiment: Industrial scale

Starting point for the optimization was a non-economical running time between one and two hours (10,000 – 15,000 litres) with a strong protein fouling blocking all the equipment in the high heating

Table 1 Optimization production regarding increasing the pre-denaturation from 95 up to 110°C [3]

	Inital situation before optimization		
	production volume	10.000-15.000 liters	
	fouling situation	very strong fouling / controll sensors fully blocked	
	denaturation temperature:	**95°C**	
	reason for production end	sensor blocking / very strong fouling / steam consumption limit	
No 1	steam regular valve start/end production	69 vs. 80 % open	

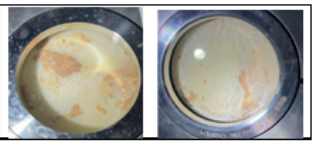
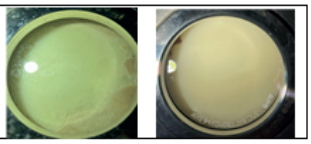
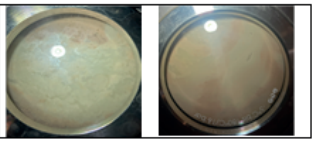
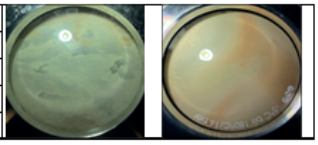
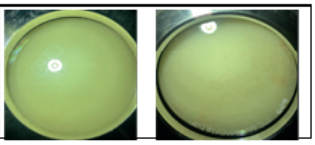
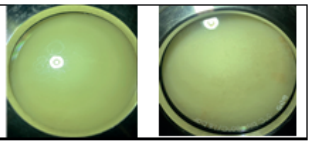
	start optimization		
	production volume	13.100 liters	
	fouling situation	strong fouling - but no blocking	
	denaturation temperature:	**100 - 102°C**	
	reason for production end	product limitation / no unsterility	
No 2	steam regular valve start/end production	69 vs. 80 % open	
	production volume	30.105 liters	
	fouling situation	strong fouling - but no blocking	
	denaturation temperature:	**100°C**	
	reason for production end	product limitation / no unsterility	
No 3	steam regular valve start/end production	69,2 vs. 70,4 % open	
	production volume	34.082 liters	
	fouling situation	strong fouling - but no blocking	
	denaturation temperature:	**100°C**	
	reason for production end	product limitation / no unsterility / no blocking	
No 4	steam regular valve start/end production	69 vs. 69,6 % open	
	production volume	15.900 liters	
	fouling situation	very strong fouling / controll sensors fully blocked	
	denaturation temperature:	**100°C**	
	reason for production end	steam consumption limit	
No 5	steam regular valve start/end production	69,9 vs. 72,4 % open	
	production volume	12.302 l/h (batch limited)	
	fouling situation	less fouling -> significant improvement	
	denaturation temperature:	**110°C**	
	reason for production end	product limitation / no unsterility / no blocking	
No 6	steam regular valve start/end production	68,6 vs. 69,3 % open	
	production volume	40.392 l (batch limitation)	
	fouling situation	less fouling -> significant improvement, best run up to now	
	denaturation temperature:	**110°C**	
	reason for production end	product limitation / no unsterility / no blocking	
No 7	steam regular valve start/end production	67,6 vs. 69,7 % open	
	production volume	16.600 l	
	fouling situation	very strong fouling	
	denaturation temperature:	**back to 100°C for validation**	
	reason for production end	steam consumption limit	
No 8	steam regular valve start/end production	69,2 vs. 85 % open	
	production volume	14.400 liters (batch limitation)	
	fouling situation	less fouling	
	denaturation temperature:	**110°C**	
	reason for production end	product limitation / no unsterility / no blocking	
No 9	steam regular valve start/end production	69 vs. 69,3 % open	
	production volume	29.200 l (batch limitation)	
	fouling situation	very less fouling also after the longer run	
	denaturation temperature:	**110°C**	
	reason for production end	product limitation / no unsterility / no blocking	
No 10	steam regular valve start/end production	68,9 vs. 68,8 % open	
	production volume	71.000 l (batch limitation)	
	fouling situation	very less fouling also after the longer run	
	denaturation temperature:	**110°C**	
	reason for production end	product limitation / no unsterility / no blocking	
No 11	steam regular valve start/end production	68,5 vs. 68,9 % open	

Fig. 11 Initial situation: strong fouling in the UHT with pre-treatment at only 95°C at all critical zones including blocking of components like temperature & pressure sensors

zones of the UHT process (fig. 11). Due to the massive precipitation, the heating temperature can no longer be maintained. The fouling layer completely covered the temperature sensor, preventing it from measuring the actual temperature of the product. Aseptic operation of the system is no longer possible. Consequently, the system had to be shut down and a long cleaning and sterilization process of up to 4 hours was required before the next 1 – 2-hour production could begin.

The production was performed with an enzyme inactivation at 95 °C.

An ideally coordinated UHT process prevents such malfunctions and ensures long production times without downtimes caused by CIP and SIP. Alternatively, a short intermediate CIP (AIC) can be done – to refresh the system and start very short afterward an additional production always under full sterile conditions.

In the following trials documented in table 1, the temperature in front of the UHT was increased in several runs up to 110 °C. The enzyme inactivation was coupled with this denaturation step in front of the decanter. The optimized temperature profile is displayed in figure 12.

In the initial experiments, the product after hydrolysis was heated to 95 °C inactivation temperature using DSI and then fed to the decanter. In the 110 °C experiments the product after hydrolysis was heated to 110 °C using DSI, then cooled to 95 °C using a tubular heat exchanger and fed to the decanter.

Enzyme inactivation step at 110 °C demonstrated a clear improvement in fouling behaviour, as evidenced by a sixfold increase in production time without the need for CIP or intermediate cleaning or respectively higher production volume in the UHT after increasing the enzyme inactivation temperature up to 110 °C. (table 1)

Due to the successful extension of the production time achieved through enzyme inactivation at 110 °C, further investigations at temperatures above 110 °C were omitted for reasons of time and cost efficiency.

Visual inspection at the sight glass (table 1) revealed distinct fouling deposits during enzyme inactivation at 95 °C and 100 °C, whereas minimal and barely visible fouling was observed at 110 °C.

The steam consumption required – displayed in table 1 – to reach the target temperature of the oat drink in the heater increased significantly during enzyme inactivation at 95 °C. Over a production volume of only 15,000 Liter, the steam control valve opened from 69 % to 80 %, indicating a substantial increase in energy demand. This trend strongly suggests the formation of fouling layers.

In contrast, during enzyme inactivation at 110 °C, the steam consumption remained largely stable. For a 71,000 Liter batch, the valve opening changed only minimally from 68.5 % at the beginning to 68.9 % at the end of production. This stability implies that no significant fouling deposits formed during this period, and heat transfer remained efficient throughout.

3.3 Product stability

The longer UHT running time brings significant economic benefits.

However, this may not be without consequences for the product quality – the following studies will reveal the "price" for profitable UHT processing. The sedimentation and colour intensity of the products compared to 95 °C and 110 °C are crucial for physical and biochemical stability.

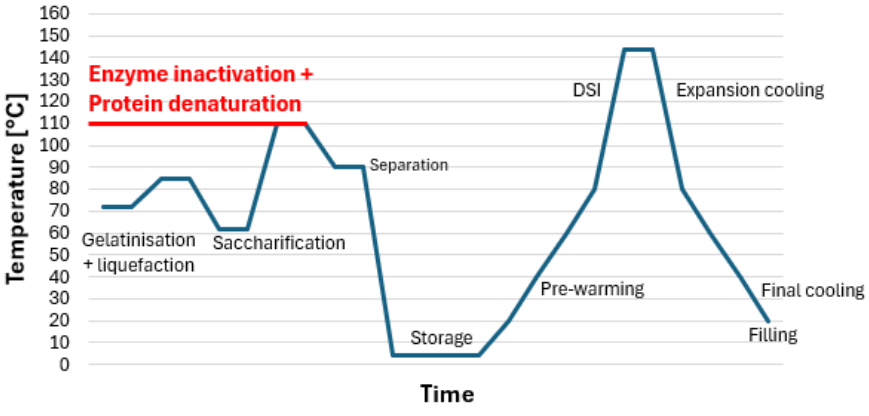


Fig. 12 Temperature profile after the combination of protein denaturation and enzyme inactivation at higher temperatures

Sedimentation tests were conducted to determine physical stability. Oat drink was poured into transparent glasses of the same volume at 95 °C, compared to a production at 110 °C. The height of the sedimentation layer was measured over time. The results displayed in figures 13 and 14 show the beginning and end, respectively. The end was defined as the time at which no further sedimentation or no change in the measured layer thickness occurred.

After a resting period of 440 minutes, no further change in sediment height was observed. The oat drink produced with enzyme inactivation at 95 °C formed an average sediment layer of 39,25 mm, whereas the product treated at

Table 2 product quality key indicators in comparison [13, 14] *taste thresholds determined in beer

	Unit		Sample Oat drink 95°C	Sample Oat drink 110°C	Taste threshold* [14]	Origin/ indicator
Colour spec-trophotometric analysis	[EBC]		19.6	25.1	-	-
Colour visual inspection	[EBC]		14.0	19.5	-	-
2-Methylbutanal	[µg/L]	*mean*	10.74	5.61	45	Strecker degr./ oxidation ind.
		sigma	0.95	0.03		
2-Methylpropa-nal	[µg/L]	*mean*	15.58	7.12	86	Strecker degr./ oxidation ind.
		sigma	1.23	0.15		
3-Methylbutanal	[µg/L]	*mean*	69.91	40.47	56	Strecker degr./ oxidation ind.
		sigma	3.37	3.70		
DMS	[µg/L]	*mean*	12.50	6.00	50	Reduction reac./ heat indicator
		sigma	0.71	4.24		
Hexanal	[µg/L]	*mean*	11.47	21.28	88	Liquid degr./ oxidation ind.
		sigma	0.63	0.88		
Furfural	[µg/L]		< 4 (LOQ)	< 4 (LOQ)	15,157	Maillard reac./ heat indicator

110 °C showed a significantly lower average sediment height of 2,58 mm.

It is hypothesized that enzyme inactivation at 110 °C resulted in a higher degree of denaturation of the protein fractions present in the oat drink. The resulting protein agglomerates were effectively removed during the subsequent separation step. As a result, significantly less sediment was formed in the final product compared to the reference oat drink treated at 95 °C.

3.4 Product quality and flavour profile

Colour was assessed using two independent methods: visual inspection and spectrophotometric analysis. Although turbidity in the samples may have introduced minor deviations, both analytical methods consistently revealed the same difference of 5.5 EBC between the samples treated at 110 °C and 95 °C (table 2).

With 5.5 EBC the difference was comparably low and is attributed more to the raw materials than to higher thermal stress. Visually, the 110 °C sample even left a more positive (whiter and creamier) impression than the 95°C sample (comparison fig. 13 & 14).

The primary objective of this investigation was to determine the criticality of elevated enzyme inactivation temperatures within the process and to assess whether such changes can be quantified analytically. Among the evaluated parameters, furfural concentration emerged as the most relevant indicator. The absence of detectable furfural displayed in table 2, with concentrations remaining below 4 µg/L, clearly indicates that the temperature increase to 110 °C does not pose a practically relevant issue in terms of product degradation or quality loss.

The measured volatile compounds exhibited slightly higher concentrations in the samples taken at 95 °C. In the context of their respective sensory thresholds and concentrations from the literature [14, 10], these differences are most likely irrelevant. Important to note is the fact that these volatiles including the hexanal are slightly volatile aromas, reduced by evaporation!

The only exception to this behaviour was observed for hexanal, highlighting its special role in the aroma perception of these samples [15]. Hexanal is a product from fatty acid oxidation of linoleic acid. Here, higher concentrations were found in the 110 °C samples – also lower than the taste threshold. The higher value is an indicator for a longer reaction time with oxygen contact.

It should be noted that due to a lack of data, the taste thresholds of the aromas in beer were used [14] and are for classification purposes only - the thresholds in oat milk will differ slightly. As described by McCarron [15] the influence of hexanal could be positively or negatively - depending on the combination with other flavours.

A positive sensory perception of oat drink is described [9, 15] as creamy, milky, nutty, umami, fruity with notes of caramel and little bit of saltiness. In contrast, undesirable sensory attributes are popcorn - like off flavour, bitterness, rancidity, excessive acidity and cheesy notes.

In figure 15, the right half of the flavour wheel represents undesirable sensory attributes, while the left half illustrates the positive flavour components typically associated with a high-quality oat drink.

Figure 15 shows a radar chart comparing the sensory profiles of oat drinks treated at 95 °C and 110 °C.

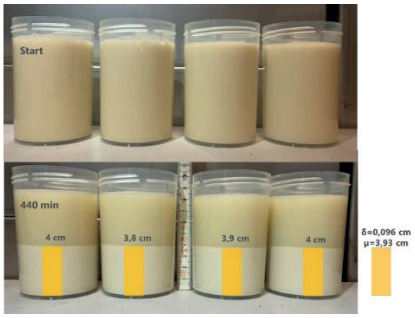


Fig. 13 95 °C

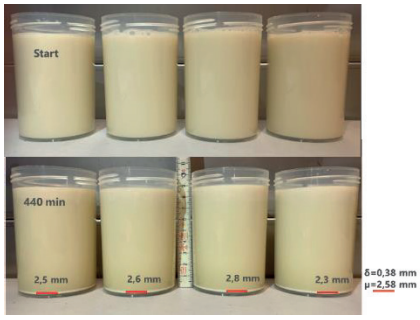


Fig. 14 110 °C

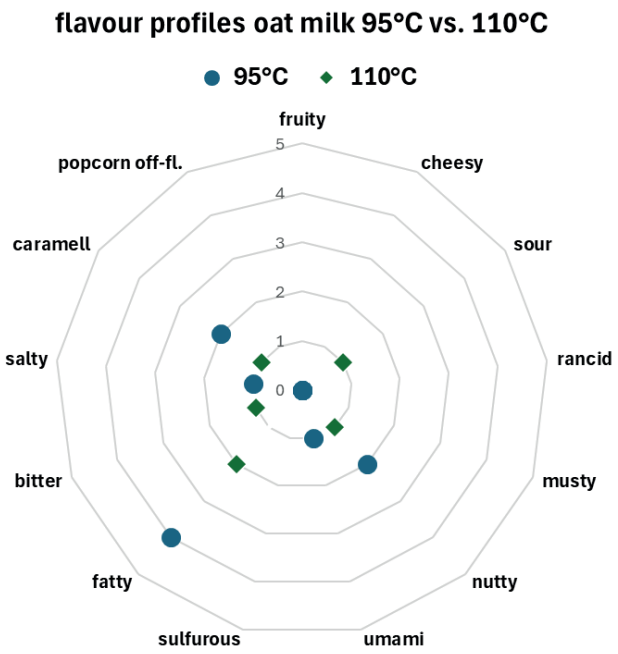


Fig. 15: flavour-profile comparison between 95°C and 110°C oat milk [13]

The oat drink treated at 95 °C showed a strong "fatty" note (intensity 4), with moderate caramel and salty impressions. The sample treated at 110 °C presented a more balanced but less intense profile, with all attributes rated low to moderate, including slight bitterness and nuttiness. This diagram clearly highlights the more pronounced sensory character - especially the fatty note - of the 95 °C sample, while the 110 °C sample appeared more neutral and less intense overall.

The statistical evaluation offers potential for further methodological refinement. Within the scope of the practical trials, however, the sample size was limited, which constrained the extent of statistical validation.

4 Conclusion

The oat drink produced from fresh oat base in the pilot scale forms soft, thick fouling layers. Fouling formation mainly occurs at temperatures above 110 °C, where the proteins in the oats presumably denature. The thick fouling layers are due to the high proportion of non-denatured proteins in the fresh produced oat base.

Fouling occurs in both direct and indirect thermal processes.

The outcomes from the literature can be confirmed with these experiments – a denaturation temperature of 110 °C is an important parameter when it comes to preventing/reducing fouling in the high temperature zone of direct UHT. With this knowledge, it should be possible to combine the inactivation of the enzymes at the same time.

This assumption was again confirmed in the commercial tests.

By increasing the pre-denaturation temperatures from 95 °C to 100 °C, a first small reduction of the fouling could be seen. The residues were still massive, but a complete blockage of the sensor system, which would have enabled a complete cleaning and sterilization, was already prevented.

By increasing the pre-denaturation temperature toward 110 °C, the production volume and duration were ultimately increased minimum sixfold. It was possible to run the plant under aseptic conditions at any time. The fouling amount also over the very long production runs was minimal in comparison to the initial pictures. Production would have been possible for an indefinite period, but the end of production was limited by the batch size.

This fits also in that what was found on to the opening grade of the steam supply valve - over the complete run the opening grade and so the steam supply was constant.

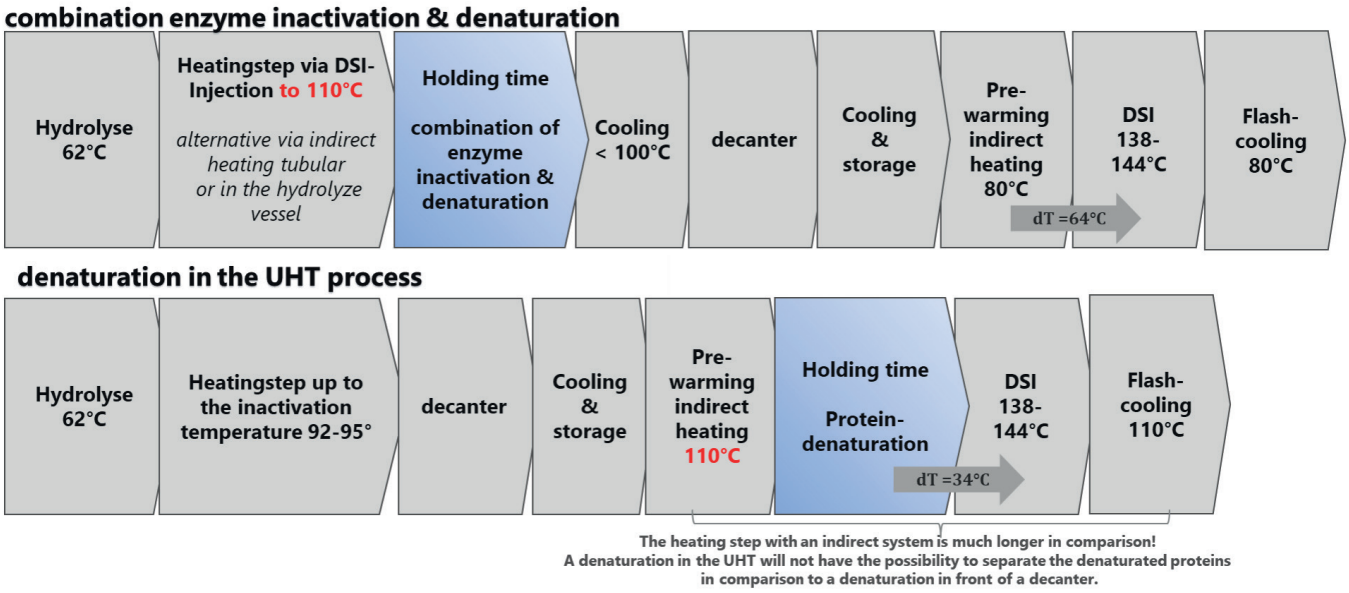


Fig. 16 process steps comparison between a denaturation in the UHT process with higher thermal stress and a denaturation in combination with the enzyme inactivation in front of a decanter

All the residues could be easily cleaned up by an AIC and the next production run can be started without a complete CIP/SIP.

Another key success factor is that the denaturation was combined with an existing thermal step to avoid unnecessarily increasing the thermal stress on the product. Furthermore, this thermal step takes place directly upstream of a decanter, which allows the precipitates to be separated there without additional cleaning effort and the risk of pollution of subsequent processes.

The alternative process would be pre-denaturation in the UHT before the high-temperature zone. In addition to the impossibility of separating the flocculated particles using a decanter, this results in a drastic reduction in the direct heating zone (80°C → 144°C → 80°C vs. 110°C → 144°C → 110°C) – since heating to the denaturation temperature would have to be achieved through an indirect heating process. Shifting the heating to the indirect UHT section increases the residence time and the thermal stress on the product. (fig. 16)

In addition to extending the running times, it was also necessary to consider the extent to which the process change would affect product quality. Contrary to expectations, there were positive developments – especially regarding the physical stability of the products. The increase in temperature had a positive effect on the homogeneity and stability of the products. The settling amount was reduced by 94 % in the 110 °C tests.

The results regarding quantification of the potential higher thermal stress showed no direct indication that the additional stress caused by the higher temperature had a consistently negative impact.

The lower concentrations of volatile aromas and the higher value for hexanal were striking. Hexanal a product, resulting from fatty acid oxidation, primarily requires oxygen and time to form – a reduction of the volatile components primarily requires a certain amount of evaporation or vaporization when these processes take place below 100 °C.

As the values become lower, the evaporation effect outweighs the formation process – especially for the DMS [20].

Both can be explained by a residence time of approximately 60 minutes in the hydrolyse vessel at 90 °C (in the 110 °C tests) vs. 62 °C (in the 95 °C tests). During this time, the oat base was transferred to the next process steps. The mash tun emptied by suction – which created perfect evaporation conditions for the volatile aromas. Furthermore, reaction products such as hexanal were able to form at the longer batch process and higher temperatures. But it looks like that the temperature was not high enough for the classical Maillard reactions.

To avoid this influence, it is necessary that the pre-warming in the hydrolyse vessel must be shift into a continuous heating step. Instead of batch heating in the tank, a tubular-, or plate heat exchanger can be used to heat the product to the denaturation/ inactivation temperature.

This process could be connected to a cooler for recuperation, which then cools the product to the decanter temperature. Alternatively, a DSI can be used – which, in turn, does not allow for energy recuperation and results in higher operating costs, but shorter up-heating process and a reduction of thermal stress.

The statistical evaluation indicates potential for further methodological refinement. Due to limited sample availability during the practical trials, the scope for comprehensive statistical validation was constrained. Future studies should consider increasing the sample size and incorporating repeated experimental trials under controlled conditions to enhance the robustness, reproducibility, and interpretability of the results.

5 Summary

The factors influencing the fouling formation of oat drinks during thermal preservation are diverse and sometimes difficult to reproduce. Fouling occurs in both direct and indirect thermal processes. Oat drinks made from a fresh produced oat base form thick layer, some of which can only be cleaned manually or increase the number of cleaning intervals into an unprofitable situation. Increased fouling formation is observed at temperatures around 110 °C.

The goal is it, to use this temperature for an ideal position of a pre- denaturation step. It is important to ensure that the thermal stress on the product is kept as low as possible; the denaturing step should therefore be integrated at a high temperature process that is already present. This process is the enzyme inactivation step which is normally only at 90 – 95 °C. The increase to the 110 °C for the protein denaturation is a moderate thermal impact.

Additionally, this process combination enables the combined separation of precipitations and insoluble oat grain components. This is not possible if the denaturation is a step in the UHT process.

With this pre-denaturation the running time in the UHT was increased from 1 – 2 hours to minimum 9 hours. Another important aspect is that, unlike before the optimization, the system did not become unsterile after the production volume was reached. This allows for a much more cost-effective, quick cleaning under sterile conditions (AIC) – allowing production to be restarted immediately afterwards.

Fortunately, the product quality did not suffer in a truly significant scale because of the temperature increase to 110 °C – on the contrary, the physical stability increased significantly. Measured colour and flavour differences were detectable but mostly irrelevant since below threshold.

An important conclusion from the results is not only to consider the supposedly critical increase in maximum temperatures, but also to keep all heating, cooling, and transfer processes as short as possible. Pre-heating in the hydrolysis tank to 90 °C with a residence time of 60 minutes had a greater impact on the product's flavour profile than increasing the temperature from 95 °C to 110 °C in the denaturation step.

Even though the results are very positive and ensure more economical production, it also means that any denaturation results

in the loss of nutritionally valuable ingredients for the consumer. Further research should attempt to optimize the process so that denaturation is not necessary. In contrast to the unalterable natural udder secretions of the dairy industry, the world of plant-based drinks potentially offers technological possibilities in product manufacturing to positively influence this. The hydrolysis process, with all the potential of different enzymes, could be a particularly promising approach here.

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Received 2 May 2025, accepted 4 August 2025