EFFECT OF PHYSICOCHEMICAL PROPERTIES OF NATIVE STARCHES ON CLEANING IN FALLING FILM AND PLANE CHANNEL FLOW EXPERIMENTS

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ABSTRACT

Reliable cleaning processes are an absolute prerequisite to ensure the production of safe foods. In particular, the cleaning of heat exchangers is a crucial process step since temperature induces the formation of strongly bound food-borne deposits. Aiming on relationships between soil-specific physicochemical properties and cleaning behaviour, four native starches of different botanical origin (maize, waxy maize, potato, wheat) were selected for plane channel flow (similar to the flow regime in plate heat exchangers) and falling film cleaning experiments. In addition, their chemical composition and swelling behaviour was analysed. Different cleaning mechanisms could be observed, whereby diffusive dissolution was identified as dominant cleaning mechanism for most starch deposits in both cleaning experiment setups. The cleaning of such soils is characterised by an initial reptation time, where the cleaning fluid penetrates the soil and no cleaning occurs, followed by a period with constant cleaning rate. Since these cleaning parameters where overlapped by swelling-induced processes, a correction model was used to identify the unaffected cleaning progress. The cleaning and swelling-induced parameters were influenced by the origin of the starch as well as by temperature and sodium hydroxide concentration of the cleaning fluid. Multivariate statistics was helpful to unravel interrelationships and interdependencies between results of cleaning experiments, and compositional and physicochemical properties.

INTRODUCTION

Motivation

In the food industry, cleaning is an essential process to protect consumers and to ensure product quality. Automated wet cleaning methods (Cleaning-in-Place, CIP) are commonly used to remove strongly adhering deposits in heat exchangers and tanks (Walton, 2008). These deposits form under the thermal impact of heat exchangers, impede heat transfer and minimise the efficiency of the heat exchanger (Goode et al., 2013). The success of cleaning and its expenditure depend on numerous factors. In addition to the operating parameters of the cleaning process or the design of the object to be cleaned, the physicochemical properties of the soil are of particular interest. Adapting the cleaning process to specific requirements of a soil offers potential savings in the environmentally damaging consumption of resources such as energy, chemicals and water. The interrelations and interdependencies between physicochemical properties and cleaning behaviour are not yet fully understood.

One of the fundamental basic ingredients in food processing is starch. It is gained from different botanical sources and mostly used to adjust stability, viscosity or texture of a product. Starch can be found e.g. in bakery products, convenience foods or confectionaries. It also plays a major role in paper production (Liu, 2005). The cleaning of starch deposits is a tedious task, since it forms strongly adhering cohesive solids.

Soil Model Systems

Current differentiations of typical food soils are primarily based on their adhesion mechanism (Epstein, 1983; Dürr & Wildbrett, 2006), failure/cleaning mechanism (Liu et al., 2006; Joppa et al., 2018) or characteristic material attributes (Dürr & Wildbrett, 2006; Bobe et al., 2008). Joppa et al. (2018) identified four cleaning mechanisms, namely diffusive dissolution, cohesive separation, viscous shifting and adhesive detachment. In their cleaning map, Fryer & Asteriadou (2009) created the link between the rheological properties of soils (non-viscous and viscous fluids, cohesive solids) and the required cleaning fluid (cold water to hot chemicals) and hence a first approach for the qualitative representation of fundamental relations between physical properties of soils and cleaning fluids. However, it only permits a rough differentiation of soils with regard to further physicochemical properties and the necessary temperature and chemistry of the cleaning fluid. The soil-specific chemical structure has only rarely been considered as the cause of a different cleaning behaviour.

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Recently, Helbig et al. (2019) showed that the cleaning behaviour of an egg yolk deposit varied due to altered molecular structures and physical properties in different cleaning fluids.

Cleaning Test Soils

In previous studies on cleaning, different components have often been used to prepare a test soil, at which the relations of interest could be investigated (e.g. Köhler et al., 2015; Otto, 2016; Fuchs et al., 2019; Helbig et al., 2019; Joppa et al., 2019; Murcek et al., 2019; Yang et al., 2019). Joppa et al. (2017) used a modified starch deposit for their cleaning investigations. The main focus of these studies was the testing of the cleanability of components, machines and plants, the scientific investigation of cleaning effects, e.g. due to changed flow configuration, and the investigation of cleaning mechanisms. However, a systematic variation of the test soil was not conducted. Palabiyik et al. (2018) investigated the rheological properties of yogurt and other soils and linked them to their cleaning behaviour. The analysis of further physicochemical properties of the soils and the identification of interactions remained unexamined. Zhang et al. (2019) specifically varied the amounts of sugar they added to whey protein soils and investigated the adhesion behaviour in a plate heat exchanger. However, the effect of the chemical composition of the complex soil on the subsequent cleaning was not analysed.

Chemical Composition of Starches

Starch is a polymeric carbohydrate consisting of α-D-glucose monomers forming two types of molecules, amylose and amylopectin. Amylose is a linear, helical molecule of $0.01 - 1$ MDa molecular mass, whose glucose units are connected through α(1→4) glycosidic bonds. In addition to the α(1→4) glycosidic bonds, the amylopectin molecule also contains α(1→6) glycosidic bonds, which form branched clusters. Amylopectin has a molecular mass of $1 - 1000$ MDa. Those structural differences result in dissimilar swelling behaviour of starches with varying amylose contents, and an increased gel strength and retrogradation of high amylose starches (Liu, 2005). Amylose also increases the adhesivity of starch (Emengo et al., 2002).

Besides carbohydrates, starch contains small amounts of water, fat, proteins, phosphorus and other mineral components. Especially the content and chemical binding of phosphorus exhibit a pronounced influence on the functional properties of starch (Singh et al., 2003; Liu, 2005).

Cleaning Behaviour and Target Figures

Joppa et al. (2017) identified diffusive dissolution as the main cleaning mechanism of solid starch layers. Xin et al. (2004) described the progress of diffusive dissolution with three typical stages: (i) The swelling stage is characterised by the reptation time t_{rep}. The cleaning fluid penetrates the soil and first chemical reactions take action but no cleaning occurs. (ii) The uniform stage shows a continuous soil removal, which can be described by a constant mean cleaning rate $\bar{\dot{m}}_s''$. (iii) The remaining soil layer is finally removed from the surface during the decay stage (Xin et al., 2004). The target figures t_{rep} and $\bar{\dot{m}}_s''$ should be determined for the investigated cleaning methods channel and falling film cleaning within this study. The time at which the decay stage starts depends on the initial soil mass $m_{s,0}''$ of the sample and is therefore only limitedly suitable for comparing the physicochemical properties that influence cleaning.

In this study, the authors show first results of linking the physicochemical properties of different native starch soils to their cleaning behaviour.

MATERIALS AND METHODS

Chemical Analysis

Four native starches (maize starch, waxy maize starch, Cargill Deutschland GmbH, Germany; potato starch, wheat starch, Agrana Beteiligungs-AG, Germany) were used in this study. The moisture content of the native starches was determined by drying at 103 °C to constant mass. Fat content was analysed by acid hydrolysis and subsequent Soxhlet extraction with petroleum ether (International Organization for Standardization, 1977), and crude protein by the Kjeldahl procedure (conversion factor 6.25) (Matissek et al., 2009). Amylose content was analysed using an Amylose/Amylopectin Assay Kit K-AMYL 12/16 (Megazyme u.c., Ireland) according to Yun & Matheson (1990). Phosphorus content was analysed by acid hydrolysis to ortho phosphate and photometric detection of phosphomolybdate complexes at 825 nm (International Organization for Standardization, 1982).

Cleaning Tests

Soiling procedure. The native starches were similarly gelatinised to provide reproducible samples. Luminescent stabilised strontium aluminate crystals were added to deionised water as tracer material and homogenised for five minutes at room temperature using a dissolver stirrer. To obtain starch pastes with similar viscosities the following concentrations of starch powder were slowly added: maize starch 4.4 g $(100\ \mathrm{g})^{-1}$; waxy maize starch 3.5 g $(100\ \mathrm{g})^{-1}$; potato starch 2.5 g $(100\ \mathrm{g})^{-1}$; wheat starch 3.5 g $(100\ \mathrm{g})^{-1}$. Gelatinisation took place in a water bath at 95 °C for 45 min while stirring at $1000\ \mathrm{min}^{-1}$. The liquid starch paste was evenly applied to stainless steel substrates (AISI 304 with a 2B finish, $R_z \leq 1$ µm, $150 \times 80\ \mathrm{mm}^2$ (plane channel) and $300 \times 100\ \mathrm{mm}^2$ (falling film)) using a pipette. The samples were finally dried at standard climate (23 °C, 50 % relative humidity) for about

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18 h. The criterion for the reproducibility of the samples was the initial soil mass $m''_{s,0}$ of the dried samples, which was set to 50 ± 5 g m^{-2}.

Test rigs. Plate heat exchangers contain narrow, flat channel flows that the processed food has to pass through. A test rig for investigation of cleaning within closed components was introduced in Schöler et al. (2009) and adapted for plane channel flow experiments in Joppa et al. (2017). The temperature-controlled cleaning fluid flowed through the plane channel with a cross-sectional area of 78×5 mm^2 with a defined bulk velocity u_b of 1 m s^{-1}. The luminescent deposits were activated with an UV-lamp through a transparent component cover and removed by the cleaning fluid from the steel substrates within the plane channel section. The intensity of the deposit was captured time- and location-resolved by a monochrome camera. The measuring section was located within a housing to avoid interferences by external light sources.

For tank cleaning in the food industry, spray balls are often used, which distribute the cleaning fluid onto the tank surface. The resulting falling film overflows the deposit and slowly removes it (Walton, 2008). The falling film experiments were conducted in a test rig, which is described in detail in Fuchs et al. (2013). The samples were clamped into a 75 ° inclined fixture and overflowed by the temperature-controlled cleaning fluid with a defined volumetric wetting rate of 2.5 m^3(h m)$^{-1}$. The cleaning progress of the UV-activated luminescent deposit is also time- and location-resolved captured by a monochrome camera. A housing surrounded the measuring section.

Cleaning Experiments

In both experimental setups, the cleaning fluid was varied in two stages with regard to temperature 25 °C and 55 °C as well as sodium hydroxide concentration c_{NaOH} of 0.0 g (100 g)$^{-1}$ (deionised water) and 2.0 g (100 g)$^{-1}$ (abbrev. T25H2O, T55H2O, T25N20 and T55N20). A centre test point (40 °C, 1.0 g (100 g)$^{-1}$, abbrev. T40N10) was investigated for each starch and experimental setup additionally. The cleaning tests ended after 1800 s.

The monochrome pictures were analysed for each time step with a Matlab script (Matlab R2017b, The MathWorks Inc.). The grey values are determined for each pixel and averaged within a range of interest (40×40 mm^2 for plane channel, 200×50 mm^2 for falling film setup) to receive the time-resolved intensity $I_{\mathrm{raw}}(t)$. The intensity was then normalised to ensure the comparability of both test setups using the formulation

$$I_{\mathrm{norm}}(t) = \frac{I_{\mathrm{raw}}(t)}{I_{\mathrm{raw}}(t=0)}. \quad (1)$$

Representative progressions of the original and the normalised intensity are given in figure 1. The increase in intensity at the beginning of the cleaning process is clearly visible. A maximum is followed by a continuous decrease in intensity. This initial increase in intensity is caused by swelling-induced processes and overlaps the actual cleaning progress.

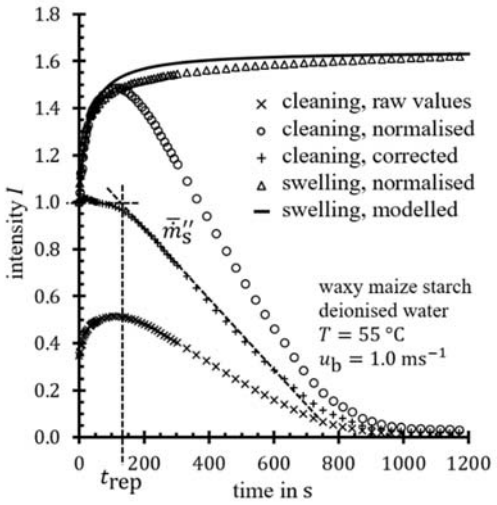

Fig. 1. Representative swelling and cleaning progression

Swelling Behaviour

Correction model. Joppa et al. (2019) have already separated the intensity increase from the cleaning progress using the correction function

$$I_{\mathrm{cor}}(t) = \frac{I_{\mathrm{norm}}(t)}{I_{\mathrm{norm,swell}}(t)}. \quad (2)$$

$I_{\mathrm{norm,swell}}(t)$ describes the swelling-induced intensity progress of the soil. According to Joppa et al. (2019), $I_{\mathrm{norm,swell}}(t)$ was described with the mathematical formulation

$$I_{\mathrm{norm,swell}}(t) = \frac{p \cdot t}{q + t} + 1. \quad (3)$$

The model parameter p represents a measure for the maximum intensity capacity and the model parameter q^{-1} describes the initial increase velocity of the intensity progress.

Swelling experiments. To capture the swelling behaviour of the starch soils, the bulk velocity u_{b} of the cleaning fluid was set to 0 by only flooding the channel with the hydrostatic pressure. For the falling film setup, the bulk velocity was minimised by reducing the inclination angle to its technical minimum of 25° and setting the volumetric wetting rate to 1.5 m^3(h m)$^{-1}$. A variation of the cleaning fluid was conducted analogically to the cleaning experiments with regard to its temperature and concentration of sodium hydroxide. The intensity of the starch deposits was recorded during swelling for 1800 s and the grey values of the monochrome pictures were determined, averaged and normalised within

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the range of interest (equation 1). A representative swelling progress is shown in figure 1. An initial increase in intensity at the beginning smoothly transforms into a plateau and stagnates.

The experimental data of the intensity progression (data not shown, n = 3) were fitted to the correction model (equation 3) by minimising the sum of error squares. The model parameters p and q^{-1} were determined for each starch and cleaning fluid composition. A dependence on the initial soil mass $m''_{s,0}$ as described by Joppa et al. (2019) was not tested, since it was kept constant.

Statistical Analyses

Analysis of variance with subsequent Tukey-B post-hoc testing at $P \leq 0.05$ were conducted for all results. A principal component analysis (PCA) was carried out based on correlation data to identify the relations between chemical properties as well as swelling and cleaning behaviour of the different starch soils. PCA reduces the data set to a small set of related variables (principal components) and was done separately for plane channel and falling film experiments. All statistical analyses were carried out by SPSS 25.0 (SPSS Inc., Chicago, Il, USA).

RESULTS AND DISCUSSION

Chemical Structure

Table 1 shows the differences in the chemical composition of the starch powders, calculated based on dry matter. While the differences in fat and protein content are small, starch powders show clear differences in phosphorus, amylopectin and amylose content. The phosphorus content was highest in potato and wheat starch (63.48 mg (100 g)$^{-1}$ and 50.07 mg (100 g)$^{-1}$, respectively). Even though both contents of phosphorus seem comparable, the binding of phosphorus also affects the functional properties of starches. In potato starch, phosphate monoesters are bound to the C-6 atoms of amylopectin molecules and contribute to high viscosity and water binding capacity. In wheat starch, on the other hand, phospholipids are adsorbed to amylose chains and limit the swelling behaviour of starch (Singh et al., 2003; Lim et al., 1994). The amylose content was highest in wheat starch with 28.18 g (100 g)$^{-1}$ total starch, followed by maize and potato starch (24.11 g (100 g)$^{-1}$ and 23.02 g (100 g)$^{-1}$, respectively). The content of amylose in maize starch was comparable to literature (25 – 28 g (100 g)$^{-1}$), whereas the contents in potato and wheat starch are usually specified with 19 – 21 g (100 g)$^{-1}$ and 25 g (100 g)$^{-1}$ (Sheldrake, 2009). In contrast, waxy maize starch almost exclusively consists of amylopectin and only a minor fraction of amylose. The determined content of amylose is slightly higher with 2.26 g (100 g)$^{-1}$ than in literature references with ≤ 1 g (100 g)$^{-1}$ (Sheldrake, 2009).

Swelling Behaviour

Figure 2 shows the experimentally determined maximum intensity capacity p for the individual test points in the plane channel setup. The trends of p showed similar behaviours for the different starches. No change within deionised water could be observed as the temperature was raised. Only with use of sodium hydroxide did p decrease. For maize and waxy maize starch, no further influence on p due to rising temperature or sodium hydroxide concentration was noticeable. Potato starch showed the overall highest values for p within deionised water. Within 2.0 g (100 g)$^{-1}$ sodium hydroxide, p decreased with an increasing temperature. For wheat starch, a similar, less pronounced effect could be observed.

The experimentally determined initial increase velocities q^{-1} are shown in figure 3 for the different starches and cleaning fluid compositions. The initial increase velocity showed similar trends for the different starches. A general increase of q^{-1} occurred when the temperature and the sodium hydroxide concentration were raised. Different swelling behaviours could be observed for maize and waxy maize starch. Changes of the fluid composition showed no significant effects on q^{-1} of maize starch. Only when the temperature of 2.0 g (100 g)$^{-1}$ sodium hydroxide was raised to 55 °C, q^{-1} increased sharply. For waxy maize starch, an increased q^{-1} could be observed for 2.0 g (100 g)$^{-1}$ sodium hydroxide at 25 °C. Especially for maize and waxy maize starch, the initial intensity increase was superimposed by a further increase and subsequent decrease of the intensity when sodium hydroxide was used as cleaning fluid. These superimpositions probably originated from further gelatinisation processes caused by sodium hydroxide, which heavily influenced q^{-1} (Roberts & Cameron, 2002). Similar influences could be observed for the falling film setup (data not shown).

Table 1. Composition of starch powders

Parameter		Waxy maize starch	Maize starch	Potato starch	Wheat starch
Dry matter,	g (100 g)$^{-1}$	88.31 ± 0.04^{ab}	88.40 ± 0.11^{a}	84.63 ± 0.08^{c}	88.08 ± 0.15^{b}
Fat *,	g (100 g)$^{-1}$	0.03 ± 0.01^{b}	0.52 ± 0.08^{a}	0.01 ± 0.00^{b}	0.47 ± 0.02^{a}
Protein *,	g (100 g)$^{-1}$	0.06 ± 0.02^{b}	0.18 ± 0.02^{a}	0.08 ± 0.00^{b}	0.19 ± 0.02^{a}
Phosphorus *,	mg (100 g)$^{-1}$	18.34 ± 2.05^{c}	19.90 ± 1.72^{c}	63.48 ± 1.06^{a}	50.07 ± 3.59^{b}
Amylose **,	g (100 g)$^{-1}$	2.26 ± 1.37^{c}	24.11 ± 1.81^{b}	23.02 ± 1.81^{b}	28.18 ± 1.38^{a}

* dry matter related content; ** whole starch related content; mean ± SD values (n = 3); values with different superscripts within a row differ significantly at $P < 0.05$

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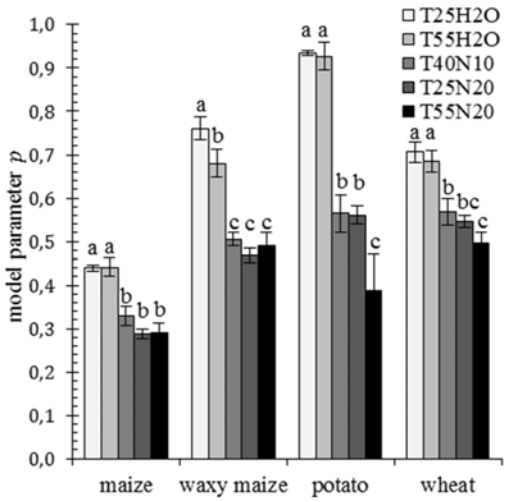

Fig. 2. Maximum intensity capacity p in plane channel flow; Mean ± SD values (n = 3); values with different letters within a starch differ significantly at $P < 0.05$

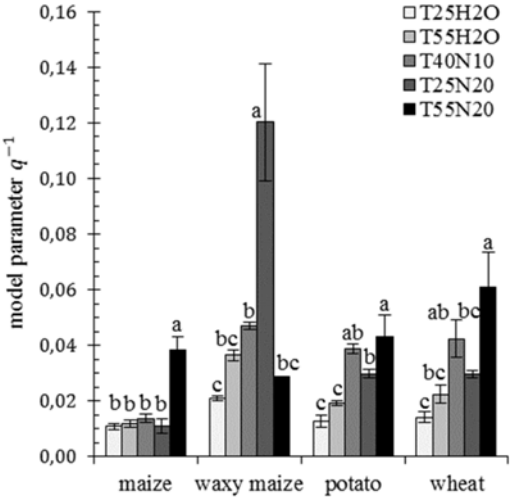

Fig. 3. Initial increase velocity q^{-1} in plane channel flow; Mean ± SD values (n = 3); values with different letters within a starch differ significantly at $P < 0.05$

Cleaning Behaviour

Figure 4 shows the reptation times (corrected by equation 2) for each starch type measured in plane channel flow and falling film experiments. The reptation time is not illustrated when no cleaning occurred ($t_{\mathrm{rep}} > 1800\ \mathrm{s}\ ;\ \bar{m}_s'' = 0$). No cleaning was observed with deionised water for most starches within both test setups. Only waxy maize starch was cleaned at 25 °C with deionised water in the falling film setup. Waxy maize and potato starch could also be cleaned with deionised water at 55 °C in both test setups. The specific quantities of t_{rep} differ for the different starches, but the overall trends tend to show similar behaviours for both test setups. Maize starch could be cleaned with $1.0\ \mathrm{g}\ (100\ \mathrm{g})^{-1}$ sodium hydroxide at 40 °C and $2.0\ \mathrm{g}\ (100\ \mathrm{g})^{-1}$sodium hydroxide at 25 °C after a long reptation time. When temperature was increased to 55 °C, t_{rep} decreased rapidly. For waxy maize starch, low overall reptation times and just a small influence of a rising temperature could be observed. t_{rep} of potato starch showed high values in deionised water at 55 °C in the plane channel setup and decreased sharply as soon as sodium hydroxide was used. For wheat starch, t_{rep} decreased with an increasing concentration of sodium hydroxide. An increasing temperature showed no further effect. The same effects occurred in the falling film setup, although the overall values of t_{rep} were higher for this test setup.

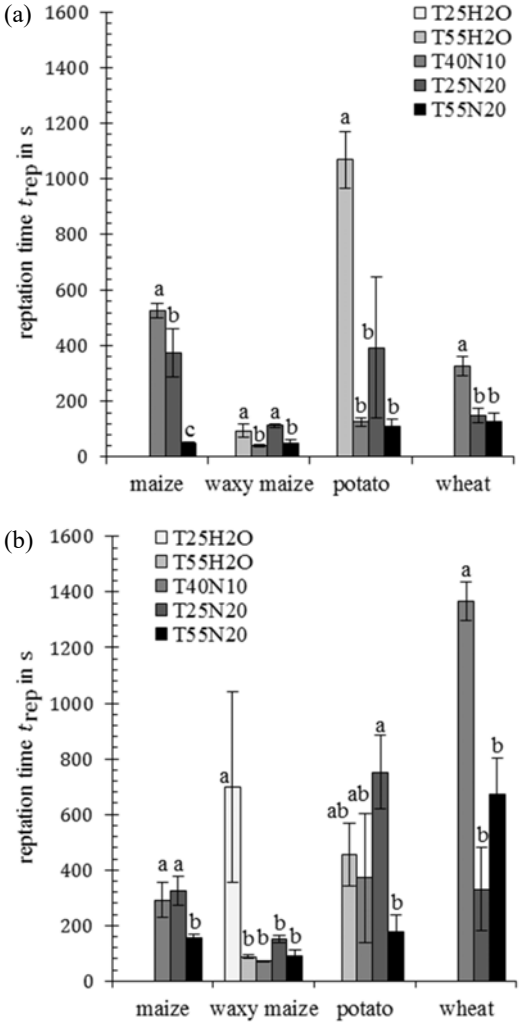

Fig. 4. Reptation time t_{rep} in plane channel flow (a) and falling film setup (b); Mean ± SD values (n = 3); values with different letters within a starch differ significantly at $P < 0.05$; t_{rep} is not shown, when no cleaning occurred for 1800 s

Figure 5 depicts the mean cleaning rate for plane channel flow and falling film experiments. The mean cleaning rate $\bar{m}_s''$ was set 0, when no

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cleaning occurred. As discussed above, no cleaning occurred for all starches except waxy maize and potato starch when only deionised water was used. The composition of the cleaning fluid showed similar effects on $\bar{\dot{m}}_s''$ of the different starches in both experimental setups (note different scaling). For maize starch, a change of sodium hydroxide concentration showed no effect on $\bar{\dot{m}}_s''$ and only a small increase could be observed when the temperature of 2.0 g $(100\ \mathrm{g})^{-1}$ sodium hydroxide was raised to 55 °C. $\bar{\dot{m}}_s''$ of waxy maize starch increased strongly with a raise of temperature for both deionised water and sodium hydroxide. Once cleaning took place, potato starch was cleaned rapidly due to an observed adhesive removal. For wheat starch, $\bar{\dot{m}}_s''$ showed the overall lowest values and could only be cleaned with sodium hydroxide at high temperatures.

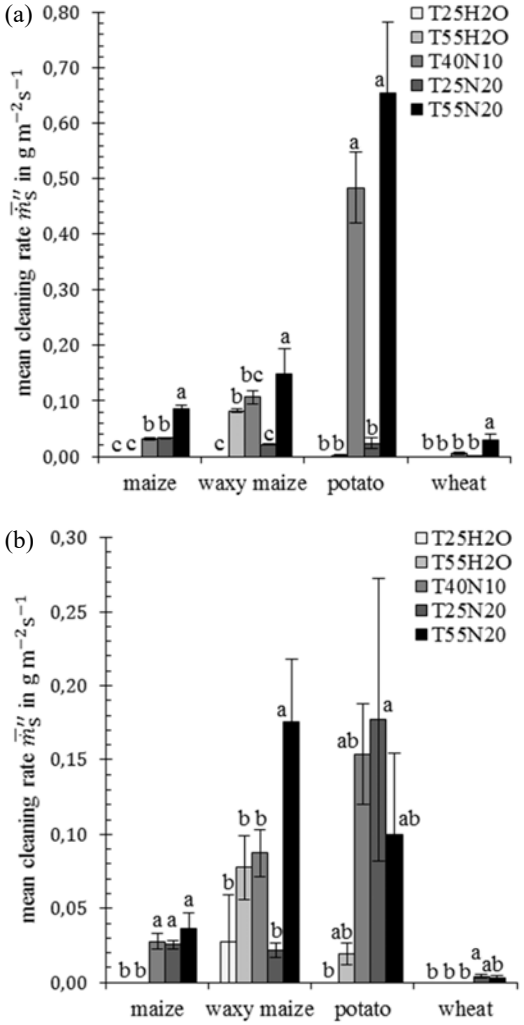

Fig. 5. Mean cleaning rate $\bar{\dot{m}}_s''$ in plane channel flow (a) and falling film setup (b); Mean ± SD values (n = 3); values with different letters within a starch differ significantly at $P < 0.05$; $\bar{\dot{m}}_s'' = 0$, when no cleaning occurred

For the waxy maize starch deposit, no differences in the cleaning rate could be observed for 55 °C, deionised water and 40 °C, 1.0 g $(100\ \mathrm{g})^{-1}$ sodium hydroxide leading to the assumption that the energy for heating the cleaning fluid can be saved when increasing the concentration of sodium hydroxide and vice versa. A similar tendency can be observed for maize starch.

Interestingly, the composition of the cleaning fluid tends to have a similar influence on the cleaning parameters in plane channel flow and falling film setup. For some starches, differences between the cleaning methods could only be observed at a few test points. The comparable effects can probably be attributed to the flow configuration, which is very similar in both cleaning processes.

Multivariate Statistical Analysis

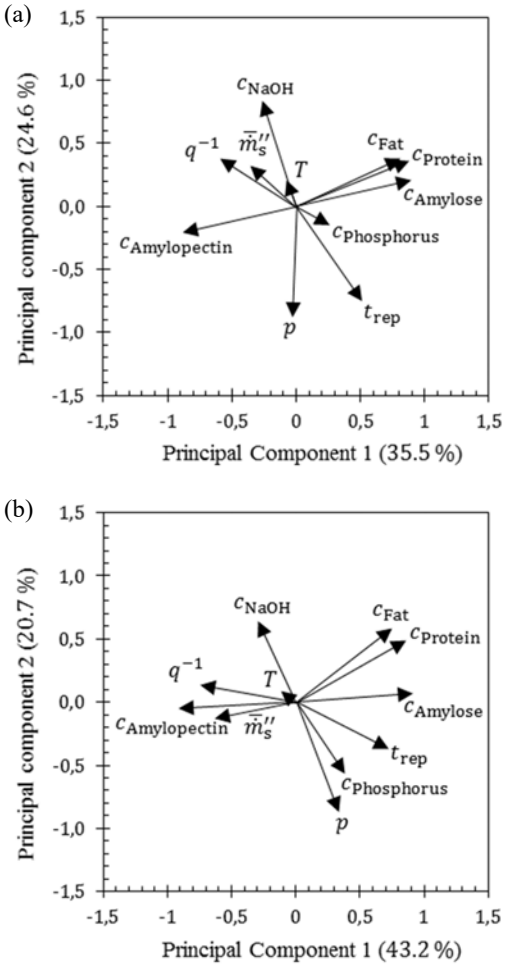

Fig. 6. Principal component plot of plane channel experiments (a) and falling film experiments (b); t_{rep} was set to 1800 s, when no cleaning occurred

The PCA of the plane channel flow and falling film experiments show a similar relationship of the cleaning parameters and the results from chemical and swelling analyses (figure 6). Both the swelling

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and cleaning parameters are related to the cleaning fluid composition as discussed above. The reptation time correlates strongly with the swelling-induced maximum intensity capacity p, which again depends negatively on the sodium hydroxide concentration of the cleaning fluid as well as the phosphorus content of the starches. The mean cleaning rate is strongly influenced by the swelling-induced initial intensity increase q^{-1}, indicating that the swelling velocity determines the cleaning velocity. Both parameters again depend positively on the sodium hydroxide concentration of the cleaning fluid and the amylopectin content of the starches. A major correlation of the temperature could not be found, since it individually influences the swelling and cleaning behaviour of the starches.

The chemical composition distinguishes the native starches depending on the different fat, protein, amylopectin and phosphorus content. Correlations between q^{-1} and the amylopectin content as well as p and the phosphorus content could be found in both experimental setups, creating a linkage between the chemical composition of the starches and their cleaning behaviour.

In the present form, the determined chemical parameters do not consider chemical reactions and structural changes of the starch deposits in contact with the cleaning fluid. It is well known that water-soluble proteins and sugars are immediately dissolved during contact with water, and molecules with large molecular masses remain in the soil layer. However, due to the influence of acidic or alkaline pH and high temperature, changes in the chemical structure are possible, e.g. denaturation, swelling and hydrolysis. To predict the cleaning behaviour based on the chemical composition, it is necessary to implement these influences of the cleaning fluid.

The correlations between the swelling-induced parameters and the cleaning behaviour show as well that the velocity of suitable reactions should be taken into account. Therefore, forthcoming analyses should aim at the time-dependent change of the chemical and physical properties of the soil upon contact with the cleaning fluid.

CONCLUSION

The aim of this study was to show the influence of physicochemical properties of starches with different botanical origins on their cleaning behaviour. It is shown that the chemical structure and the composition of the cleaning fluid have different effects on the swelling behaviour of different starches, leading to a different cleaning behaviour. The influence of the chemical starch composition on the initial increase velocity and furthermore on cleaning is particularly to be emphasised here.

In the literature, further physicochemical properties are already mentioned which have an influence on the cleaning behaviour of various soils. Within this study it was not yet possible to characterise all these physicochemical properties. Further investigations in this direction are part of future work and will be included in the evaluations.

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NOMENCLATURE

Abbreviation

PCA	principal components analysis
T25H2O	$T = 25$ °C, deionised water
T55H2O	$T = 55$ °C, deionised water
T40N10	$T = 40$ °C, $c_{\mathrm{NaOH}} = 1.0$ g (100 g)$^{-1}$
T25N20	$T = 25$ °C, $c_{\mathrm{NaOH}} = 2.0$ g (100 g)$^{-1}$
T55N20	$T = 55$ °C, $c_{\mathrm{NaOH}} = 2.0$ g (100 g)$^{-1}$

Latin Symbols

c	concentration, g (100 g)$^{-1}$
I	intensity, dimensionless
m	mass, g
$\bar{\dot{m}}$	mean cleaning rate, g s^{-1}
p	maximum intensity capacity, dimensionless
P	P-value
q^{-1}	initial increase velocity, s^{-1}
t	time, s
T	temperature, °C
u	velocity, m s^{-1}

Subscript

0	initial
b	bulk
norm	normalised
raw	original
rep	reptation
s	soil
swell	swelling

Superscript

´´	per area, m^{-2}

REFERENCES

Bobe U, Sommer K, Peukert W, Beck U, Schaule G. 2008. Die Reinigbarkeit technischer Oberflächen im immergierten System. Chemie Ingenieur Technik. 80:1349–1349.

Dürr H, Wildbrett G. 2006. Grundvorgänge bei Verschmutzung und Reinigung. In: Wildbrett

ISBN: 978-0-9984188-1-0; Published online www.heatexchanger-fouling.com

G, editor. Reinigung und Desinfektion in der Lebensmittelindustrie. 2nd ed. Hamburg: Behr's Verlag.

Emengo FN, Chukwu SER, Mozie J. 2002. Tack and Bonding Strength of carbohydrate-based Adhesives from different botanical Sources. International Journal of Adhesion and Adhesives. 22:93–100.

Epstein N. 1983. Thinking about Heat Transfer Fouling: A 5 × 5 Matrix. Heat Transfer Engineering. 4:43–56.

Fryer PJ, Asteriadou K. 2009. A Prototype Cleaning Map: A Classification of Industrial Cleaning Processes. Trends in Food Science & Technology. 20:255–262.

Fuchs E, Boye A, Stoye H, Mauermann M, Majschak J-P. 2013. Influence of the Film Flow Characteristic on the Cleaning Behaviour. Proceedings of International Conference on Heat Exchanger Fouling and Cleaning. Budapest.

Fuchs E, Kricke S, Schöhl E, Majschak J-P. 2019. Effect of industrial scale stand-off distance on water jet break-up, cleaning and forces imposed on soil layers. Food and Bioproducts Processing. 113:129–141.

Goode KR, Asteriadou K, Robbins PT, Fryer PJ. 2013. Fouling and Cleaning Studies in the Food and Beverage Industry Classified by Cleaning Type. Comprehensive Reviews in Food Science and Food Safety. 12:121–143.

Helbig M, Zahn S, Böttcher K, Rohm H, Majschak J-P. 2019. Laboratory Methods to Predict the Cleaning Behaviour of Egg Yolk Layers in a Flow Channel. Food and Bioproducts Processing. 113:108–117.

International Organization for Standardization. 1977. Starches, native or modified – Determination of total fat content. (ISO 3947:1977).

International Organization for Standardization. 1982. Starches and derived products; Determination of total phosphorus content; Spectrophotometric method. (ISO 3946:1982-12).

Joppa M, Köhler H, Kricke S, Majschak J-P, Fröhlich J, Rüdiger F. 2019. Simulation of jet cleaning: Diffusion model for swellable soils. Food and Bioproducts Processing. 113:168–176.

Joppa M, Köhler H, Rüdiger F, Majschak J-P, Fröhlich J. 2017. Experiments and Simulations on the Cleaning of a Swellable Soil in Plane Channel Flow. Heat Transfer Engineering. 38:786–795.

Joppa M, Köhler H, Rüdiger F, Majschak J-P, Fröhlich J. 2018. Prediction of Cleaning by Means of Computational Fluid Dynamics: Implication of the Pre-wetting of a Swellable Soil. Heat Transfer Engineering. 0:1–11.

Köhler H, Stoye H, Mauermann M, Weyrauch T, Majschak J-P. 2015. How to assess Cleaning? Evaluating the Cleaning Performance of Moving Impinging Jets. Food and Bioproducts Processing. 93:327–332.

Lim, S-T, Kasemsuwan, T, Jane, J-L. 1994. Characterization of phosphorus in starch by 31P-nuclear magnetic resonance spectroscopy. Cereal Chemistry. 71(5):488–493.

Liu Q. 2005. Understanding Starches and Their Role in Foods. In: Cui, S W, editor. Food Carbohydrates: Chemistry, Physical Properties, and Applications. 1st ed. Boca Raton: CRC Press. 309–356.

Liu W, Fryer PJ, Zhang Z, Zhao Q, Liu Y. 2006. Identification of Cohesive and Adhesive Effects in the Cleaning of Food Fouling Deposits. Innovative Food Science & Emerging Technologies. 7:263–269.

Matissek R, Steiner G, Fischer M. 2009. Lebensmittelanalytik. 4th ed. Berlin: Springer.

Murcek R, Schöhl E, Köhler H, Boye A, Gold S. 2019. Development of a Method to Determine Normal and Shear Stress Necessary to Remove a Swollen Soil from a Surface. Food and Bioproducts Processing. 113:86–92.

Otto C. 2016. Reinigungsverhalten modifizierter Lebensmittelinhaltsstoffe. Dissertation. Dresden: TU Dresden

Palabiyik I, Lopez-Quiroga E, Robbins PT, Goode KR, Fryer PJ. 2018. Removal of yield-stress Fluids from Pipework using Water. AIChE Journal. 64:1517–1527.

Roberts S.A., Cameron R.E. 2002. The effect of concentration and sodium hydroxide on the rheological properties of potato starch gelatinisation. Carbohydrate Polymers. 50:133-143.

Schöler M, Fuchs T, Helbig M, Augustin W, Scholl S, Majschak J-P. 2009. Monitoring of the Local Cleaning Efficiency of Pulsed Flow Cleaning Procedures. Proceedings of International Conference on Heat Exchanger Fouling and Cleaning VIII. Schladming

Sheldrake P. 2009. Starch. In: Imeson, A. editor. Food Stabilisers, Thickeners and Gelling Agents. Ames, Iowa: Blackwell Pub. 293–324.

Singh N, Kaur L, Gill BS, Singh J, Sodhi NS. 2003. Morphological, Thermal and Rheological Properties of Starches from different Botanical Sources. Food Chemistry. 81:219–231.

Walton, M. 2008. Principles of Cleaning-in-Place (CIP). In Tamime, A. editor. Cleaning-in-Place: Dairy, Food and Beverage Operations. 3rd ed. Oxford: Blackwell

Xin H, Chen XD, Özkan N. 2004. A Mathematical Model of the Removal of Milk Protein Deposit. In: Heat Exchanger Fouling and Cleaning: Fundamentals and Applications. 22: 158–168.

Yang J, Kjellberg K, Jensen BBB, Nordkvist M, Gernaey KV, Krühne U. 2019. Investigation of the Cleaning of Egg Yolk Deposits from Tank Surfaces using Continuous and Pulsed Flows.

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Food and Bioproducts Processing. 113:154–167.

Yun S-H, Matheson NK. 1990. Estimation of Amylose Content of Starches after Precipitation of Amylopectin by Concanavalin-A. Starch - Stärke. 42:302–305.

Zhang BY, Lu J, Huang J-Y. 2019. Effect of sugar on the fouling behavior of whey protein. Food and Bioproducts Processing. 113:2–9.

ISBN: 978-0-9984188-1-0; Published online www.heatexchanger-fouling.com