Original article

**Laminar flow cleaning of gelatinised, partially hydrolysed starch**

Susann Zahn, Clemens Otto & Harald Rohm*

Chair of Food Engineering, Technische Universität Dresden, 01062, Dresden, Germany

(Received 4 July 2019; Accepted in revised form 31 July 2019)

**Summary**
The cleanability of food contact materials is, among others, determined by the physico-chemical properties of the soiling material. In the current study, starch of different origin was gelatinised and partially hydrolysed with diastase. The degree of hydrolysis was determined as the reducing capacity in terms of dextrose equivalents, and by the changes in apparent viscosity and surface tension. After spreading the starch paste on electropolished stainless steel coupons and subsequent drying, the removal was studied with a laboratory flow cell. These cleaning tests revealed a higher cleaning effectivity for smaller dextrins, which can be attributed to corresponding changes in solubility. Furthermore, the addition of commercially available diastase to demineralised water increased the cleaning effectivity of starch and dextrin soils at 25 °C. The results indicate that smaller starch breakdown products require reduced energy for removal so that cleaning processes can be adequately adjusted.

**Keywords**
Cleaning, diastase, flow cell, fouling, stainless steel, starch.

**Introduction**

The fundamental knowledge of product and machinery design opens the way to creating tailor-made cleaning protocols, which are a prerequisite for hygienic food production. To ensure efficient and sustainable cleaning, the adhesive forces between a particular soil and a surface must be overcome with minimum efforts concerning, for example, mechanical and thermal energy, and the use of chemicals. The requirements for removing food polymers such as starch depend on molecule size and are linked to different adhesion models. According to the DVLO theory, interaction forces (i.e. van der Waals or electrostatic forces) decrease when particles are smaller (Visser, 1995; Fryer & Asteriadou, 2009). In contrast, the rheological model of Carre & Schultz (1984) relates adhesive and cohesive properties of polymers to the cross-linking degree. Weak boundary layers may result from a higher degree of polymer cross-linking and a reduced energy dissipation that occurs when bonds between low molecular mass polymers and surface fail (Fourche, 1995).

Enzymatic modification is a powerful tool to alter the techno-functional properties of polymers such as solubility or water and oil-binding capacity. In the case of starch, enzymatic hydrolysis reduces molecule size and the viscosity of respective solutions. The degree of hydrolysis (DH) can be expressed in terms of dextrose equivalents (DE), inversely related to the size of the resulting maltodextrins, and to the viscosity of solutions at similar concentration (Lopez et al., 2010; Sun et al., 2010).

Several effects related to starch removal can be attributed to differences in the properties of the soiling agent (solubility, viscosity) and, for industrial adhesives, it is especially a starch molecular mass of $4 \times 10^4$–$4 \times 10^7$ Da that is known to play an important role (Jurado Alameda et al., 2011). When particles are coated with polymers of varying molecular mass, the presence of longer polymer chains may increase adhesive interactions (Toure et al., 2011). Studies on mass transport in cross-flow filtration showed that transport phenomena also depend on particle size: particle sizes $<0.1 \mu$m resulted in diffusive mass transport while, for particles larger than approx. $0.5 \mu$m, primarily a shear-induced transport can be expected (Kim & Digiano, 2009).

The chemistry of a particular soil also determines the fluid that should be used for cleaning. Enzymes are excellent cleaners for starch and protein deposits and can be used instead of highly alkaline solutions where they provide environmental and economic benefits (Antony et al., 2014; Jurado Alameda et al., 2014, 2015). Amylases are part of laundry and automatic dishwasher detergents for cleaning up starch residues.
Cleaning of hydrolysed starch S. Zahn et al.

Materials and methods

Materials

Test coupons (electropolished stainless steel 316L, 40 x 20 x 1 mm²) were washed in 0.25 mol L⁻¹ NaOH under sonication (15 min, 45 kHz, 160 W), rinsed in deionised water and dried on filter paper.

Based on previous investigations (Zahn et al., 2012; Otto et al., 2014), three native starches (approx. 120 g kg⁻¹ moisture, approx. 850 g kg⁻¹ starch) were selected: Native corn starch (NC, 290 g kg⁻¹ amylose), native waxy corn starch (NWC, 30 g kg⁻¹ amylose) and native wheat starch (NW, 260 g kg⁻¹ amylose) were from Agrana Stärke GmbH (Gmünd, Austria). Dry matter was determined by oven drying at 105 °C to mass constancy, and starch and amylose content were analysed using enzymatic test kits (Megazyme Ltd., Bray, Ireland; McCleary et al., 1997).

Diastase, a mixture of a-amylase (EC.3.2.1.1) and β-amylase (EC.3.2.1.2) from Aspergillus oryzae, pH optimum: 5–6, was from Sigma-Aldrich GmbH, Munich, Germany. Declared activity of the enzyme was 5800 U g⁻¹, with 1 U corresponding to the amount of enzyme that liberates 1 μmol min⁻¹ maltose at pH 6.0 and 25 °C.

Preparation of the soiling material and starch hydrolysis

Based on literature suggestions (Detry et al., 2011), the starches were suspended in deionised water at 10 g L⁻¹. After stirring for 12 h at room temperature, the starches were gelatinised by heating to 90 °C for 10 min and then cooled to room temperature. 100 μL of the liquid soil, containing 1 mg starch, was pipetted onto a 2 cm² area of the steel coupons and then dried at 55 °C for 1 h in an oven.

Another set of test soils was prepared by hydrolysing starch with diastase. As recommended by Jurado Alameda et al. (2014), 0.041 U enzyme per mg starch were added to gelatinised starch. Incubation was carried out in a D8GH water bath (ThermoHaake GmbH, Karlsruhe, Germany) at 25 °C for predefined periods of time. The reaction of the enzyme was stopped by heating the mixture to 90 °C for 10 min.

Analysis of the starch test soils

Dextrose equivalents

The degree of hydrolysis (DH) was determined in triplicate using the dinitrosalicylic acid (DNS) method (Miller, 1959). 0.5 mL hydrolysed sample was pipetted into a test tube, and 0.5 mL DNS solution was added. The mixture was boiled for 5 min and immediately cooled in ice water. Absorbance was measured at 504 nm using a Lambda 2S UV/VIS spectrophotometer (Perkin-Elmer GmbH, Rodgau, Germany) with glucose (0–5 mg mL⁻¹) as calibration standard. Dextrose equivalents (DE) were calculated as follows:

\[
DE = 100 \times \frac{(\text{glucose of reducing sugar})(\text{dry solid mass})^{-1}}{\text{g}}.
\]

Rheological and surface tension measurements

The time course of gelatinised starch hydrolysis was monitored by recording the torque at a ST24 three-blade stirrer during continuous rotation in a TEZ180 cup geometry of a Physica MCR 300 rheometer (Anton Paar Germany GmbH, Graz, Austria). Temperature was set to 25 °C, and the stirrer tool was calibrated as described previously (Krush & Rohm, 2004). Rotational speed of the vane blade was 150 r.p.m. for 60 min.

Surface tension of the gelatinised starches was measured with a DCA111 tensiometer at 25 °C in duplicate (DataPhysics Instruments GmbH, Filderstadt, Germany) using the Wilhelmy plate technique. The plate was attached to the instrument microbalance and immersed into the respective system at 2 mm min⁻¹. Interfacial tension was calculated from the wetting force using the instrument software.

Solubility

Solubility of the gelatinised starches was measured in triplicate as described by Leach et al. (1959), with few modifications. After defined hydrolysis time, gelatinised...
starch was transferred into 50 mL conical tubes and centrifuged at 5000 g and 20 °C for 15 min. Subsequently, 5 mL aliquots of the supernatant were dried overnight at 105 °C. Solubility (%) is defined as the gravimetrically determined fraction of the starch that was present in the supernatant.

Cleaning experiments
Cleaning experiments were carried out in quadruplicate using a continuous flow cell system (Otto et al., 2016) consisting of a 50 mL reservoir with a magnetic stirrer for the cleaning fluid, a peristaltic pump, the cell with an effective flow channel of $40 \times 20 \times 2 \text{ mm}^3$, and connecting tubes (Figure S1). After fixing the soiled stainless steel coupon in the flow cell, continuous cleaning was performed at a flow rate of 54 mL min$^{-1}$ (Reynolds number, 40; average shear stress, 54 mPa; Otto et al., 2014) at 25 °C for 2–60 min by circulating the cleaning liquid through the cell. The cleaning liquid was either deionised water or, in case of enzymatic cleaning, a diastase solution (1–4 g L$^{-1}$). After the cleaning process, the coupons were removed from the flow cell, dried for 1 h at 55 °C and then weighed using the microbalance of the DCAT 11 tensiometer. Gravimetric cleaning effectivity after 2 or 60 min (CE$_{G,t=2 \text{ min}}$ or CE$_{G,t=60 \text{ min}}$, respectively) was calculated:

$$CE_{G,t} = 100 \left[ 1 - \frac{(m_R - m_U)(m_I - m_U)^{-1}}{m_R} \right]$$

Here, $m_R$ is the mass of the soiled coupon after cleaning, $m_I$ is the initial mass of soiled coupon before cleaning, and $m_U$ is the mass of the unsoiled dry coupon.

Results and discussion
Partial starch hydrolysis with diastase
Figure 1 depicts the progress of enzymatic starch hydrolysis at 25 °C, expressed in terms of dextrose equivalents. After 1-h incubation, the DH of native waxy corn starch was 29.6 ± 0.2 DE, followed by native corn starch (DE = 25.5 ± 0.2) and native wheat starch (DE = 24.3 ± 0.3) (complete hydrolysis is DE = 100). In the strict sense, DE reflects the relative amount of free reducing ends in a mixture of polyglucose chains. However, for a particular DE, molecule size differs between linear (amylose) and branched polymers (amylopectin). The more pronounced hydrolysis of NWC can therefore be attributed to its higher content of amylopectin, and to the fact that the hydrolytic activity of amylolytic enzymes (including $\alpha$-amylase from Aspergillus oryzae, which attacks non-crystalline regions in the starch molecule) is about twice as high towards amylopectin than towards amylose (Tanaka & Hoshino, 1999).

Expressed as torque normalised to the torque of the reference gelatinised starch pastes, Fig. 1 also shows the impact of enzymatic hydrolysis on apparent viscosity of the gelatinised solutions. It is evident that apparent viscosity decreases significantly during hydrolysis of all starch types as low-molecular breakdown products (maltose and dextrins) are formed. It can be concluded that the fraction of amylpectin, which is much higher in case of NWC starch, strongly contributes to viscosity decay rate. We have, however, no explanation for the reproducible increase of corn starch viscosity during initial hydrolysis. Although Sorba & Sopade (2013) reported a drop in the viscosity of waxy corn starch during hydrolysis by $\alpha$-amylase at starch concentrations of 3–20 g 100 g$^{-1}$, our results indicate that viscosity is not systematically related to hydrolysis for different starch types.

Solubility is an important property of any soiling material that correlates with its cleaning behaviour but also with, for instance, viscosity, surface tension and
molecule size (Emengo et al., 2002; Jurado Alameda et al., 2011). Solubility of the gelatinised starches ranged from 10.3 ± 0.8% for wheat starch to 56.3 ± 1.7% for waxy corn starch (Fig. 2). Hydrolysis caused a significant increase in the solubility of the cereal starches to 67.0 ± 0.9%, 77.8 ± 0.3% and 97.2 ± 1.7% for NW, NC and NWC starch, respectively, with most of this increase occurring in the first stage of hydrolysis, that is, within 15 min. Generally, solubility depends on interactions between starch chains; a change in solubility of hydrolysates from the same starch source is affected not only by chain length but also by molecule size, amylose content and the degree of branching (Lopez et al., 2010; Uthumporn et al., 2010). For instance, Mukerjea et al. (2007) who determined solubility for several starches found that, depending on starch type, this measure follows the order waxy corn starch > corn starch > wheat starch.

It is known that hydrolysis also affects the interaction of water molecules with hydrophilic starch groups and adhesion to solid surfaces (Adhikari et al., 2007). The surface tension of the 10 g L⁻¹ cereal starch solutions was in the range of 69–62 mN m⁻¹, and decreased with ongoing hydrolysis (Fig. 2). The reduction can be attributed to the accumulation of molecules at the air/water interface (Jurado Alameda et al., 2011) and indicates that smaller maltodextrins are more surface-active. This is supported by Prochaska, Kędziora, Thanh, & Lewandowicz (2007), who detected a significant reduction in surface tension of chemically modified starches compared to deionised water. In contrast, Rodriguez et al. (2006) reported only a slight or non-existent reduction of the surface tension of gelatinised starch, so that wetting behaviour and adhesion are not improved.

Cleaning of partially hydrolysed starch residues

Figure 3 shows the cleaning effectivities achieved during 2 min cleaning of steel coupons that were soiled with starch solutions of different DH: CEₜ,₂ min increased with increasing starch degradation (i.e. higher DE) for all starches, especially at the beginning of hydrolysis. In addition, the time course of CEₜ,₂ min mirrors that of the solubility measurements (see Fig. 2). The soil removal was most pronounced for hydrolysed NWC starch residues (CEₜ,₂ min > 97%) while NW starch residues were removed by 62% at maximum. No significant difference in CEₜ,₂ min was observed between the NW and NC starch residues incubated for 30 min. These starches are also similar with respect to their DH, and in apparent viscosity and solubility. This suggests that the cleaning results can be interpreted by the physico-chemical properties of the soiling material. In view of the fact that amylose is linear and forms strong films but that amylopectin exhibits a branched structure and forms rather weak films, it was suggested that amylose is mainly responsible for the adhesive effect, whereas waxy corn starch is easier to remove (Emengo et al., 2002). Weaker bonds within a starch residue react more pronounced on thermal, chemical and mechanical stress caused by a cleaning fluid, and are therefore responsible for a higher cleaning effectivity. Emengo et al. (2002) also studied the adhesion of carbohydrates based adhesives from corn starch. They found that depending on heat treatment intensity, the adhesive strength decreased when average molar masses were below 2.3 × 10⁶ g mol⁻¹, and attributed this effect to the smaller size of glycosidic starch chains.

The plot of cleaning effectivity against solubility shows an almost linear dependency, with higher values for prolonged hydrolysis (Fig. 3). Starch hydrolysis for 15 or 30 min was responsible for a quantitatively similar increase in CEₜ,₂ min and solubility for NC and NW starch whereas, in case of NWC starch, the increase of CEₜ,₂ min caused by hydrolysis was

![Figure 2](image-url)
higher than solubility increase. The same trend in both measures indicates that starch removal by laminar flow is largely based on diffusive transport effects. In line with results of experiments with different flow rates (Otto et al., 2014) it can be stated that, in the particular case, shear-induced flow contributes only marginally to cleaning effectivity.

In prolonged, 60 min cleaning tests with water at 25 °C, cleaning effectivity was higher than after 2 min only for NWC starch. When using the other unhydrolysed, and all hydrolysed starches as soiling material, only insignificant effects of cleaning time on cleaning effectivity were observed (Fig. 4). The results are in line with Fryer & Asteriadou (2009) who stated that cohesive soil layers are only moderately removed with cold water, because substantial physical bonds are to overcome. For oatmeal residues, Keidel et al. (2005) demonstrated that cleaning with tap water (55 °C, pH 7.3; 3.4 mmol L⁻¹ CaCO₃) is only efficient after 60 min when long swelling times are ensured.

**Enzymatic cleaning**

In preliminary experiments with diastase solutions as cleaning liquid, NW starch with intermediary cleaning effectivity (see Fig. 3) was used as soiling substrate. To determine the effect of diastase concentration on CE₇, t=2 min, the amount of enzyme in the cleaning solution was varied from 0 to 5 g L⁻¹ (i.e. 0–29 U mL⁻¹). Independent of concentration, diastase did not affect cleaning effectivity of both unhydrolysed and partially hydrolysed wheat starch (0 and 8 DE, respectively) when cleaning time was limited to 2 min. The respective cleaning effectivities were insignificantly different and ranged between 0.4 ± 2.7% and 5.4 ± 3.3% (0 DE WS), and between 49.2 ± 3.8% and 52.6 ± 2.5%

---

**Figure 3** Dependency of the cleaning effectiveness CE₇, t=2 min on starch hydrolysis (expressed as dextrose equivalents, left chart) and solubility of partially hydrolysed starch solutions (right chart). Circles, corn starch; squares, waxy corn starch; triangles, wheat starch. Cleaning data are arithmetic mean ± standard deviation from (n = 4) replicate measurements.

**Figure 4** Comparison of cleaning effectivities CE after 2 min and 60 min cleaning for unhydrolysed and partially hydrolysed starch. Circles, corn starch; squares, waxy corn starch; triangles, wheat starch. Data are arithmetic mean ± standard deviation from (n = 4) replicate measurements.

**Figure 5** Cleaning effectiveness CE₇, t=60 min (%) of unhydrolysed starch and 15 min hydrolysed starch residues. Cleaning liquid: white bars, water; black bars, 4 g L⁻¹ diastase solution. Cleaning data are arithmetic mean ± half deviation from duplicate measurements.
(8 DE WS). Jurado Alameda et al. (2011, 2015) reported that a concentration of 1 g L\(^{-1}\) \(\alpha\)-amylase solution improves the removal at higher cleaning times and mild cleaning conditions, and that increased temperatures up to 60 °C further enhanced the cleaning effectiveness.

Figure 5 presents the cleaning effectivities of starch and hydrolysed starch after 60 min cleaning with either water or 4 g L\(^{-1}\) diastase: cleaning effectivity depends on the starch type, and is affected by hydrolysis degree and the type of the cleaning fluid. With 4 g L\(^{-1}\) diastase, CE of unhydrolysed starch was in the order of NC < NW < NWC but, for hydrolysed residues, in the order of NW < NC < NWC. Dextrin residues with a molar mass less than 4 \(\times 10^3\) g mol\(^{-1}\) could be easier removed than starch residues with a molar mass of about 10\(^6\) g mol\(^{-1}\), because of a water solubility increase that is associated to lower molar mass (Tanaka & Hoshino, 1999; Emengo et al., 2002; Toure et al., 2011). As compared to water, the use of diastase solution improved CE\(_{G,t}\) for all tested soils.

**Conclusion**

The enzymatic hydrolysis of 10 g L\(^{-1}\) starch solutions was analysed by the DE value, apparent viscosity and surface tension. A decrease of molecular mass or increased branching (e.g. waxy corn starch) enhanced starch solubility, suggesting that intermolecular attraction forces (e.g. van der Waals) increase with higher chain length. In addition, the comparison of cleaning results of partially hydrolysed starch residues and their solubility data implies that lower molecular mass residues were easier removed from stainless steel. Starch removal predominately results from swelling and diffusive mass transport. Furthermore, the addition of commercially available diastase to water as cleaning fluid improved the cleaning effectivity of starch and dextrin soils at 25 °C. The results indicate that lower molecular mass starch residues require a lower cleaning effort.

**References**

Adhikari, B., Howes, T., Shrestha, A. & Bhandari, B.R. (2007). Effect of surface tension and viscosity on the surface stickiness of carbohydrate and protein solutions. *Journal of Food Engineering*, 79, 1136–1143.

Antony, N., Balachandran, S. & Mohanan, P.V. (2014). Effect of surfactants on catalytic activity of diastase \(\alpha\)-amylase. *Journal of Surfactants and Detergents*, 17, 703–708.

Carre, A. & Schultz, J. (1984). Polymer-Aluminium adhesion II. Role of the adhesive and cohesive properties of the polymer. *Journal of Adhesion*, 17, 135–156.

Detry, J.G., Sindic, M., Servais, M.J. et al. (2011). Physico-chemical mechanisms governing the adherence of starch granules on materials with different hydrophobicities. *Journal of Colloid and Interface Science*, 355, 210–221.

Emengo, F.N., Chukwu, S.E.R. & Mozie, J. (2002). Tack and bonding strength of carbohydrate-based adhesives from different botanical sources. *International Journal of Adhesion and Adhesives*, 22, 93–100.

Fouche, G. (1995). An overview of the basic aspects of polymer adhesion. Part I: fundamentals. *Polymer Engineering Science*, 35, 957–967.

Fryer, P.J. & Asteriadou, K. (2009). A prototype cleaning map: a classification of industrial cleaning processes. *Trends in Food Science and Technology*, 20, 255–262.

Gurung, N., Ray, S., Bose, S. & Rai, V. (2013). A broader view: microbial enzymes and their relevance in industries, medicine, and beyond. *BioMed Research International*, Article, 329121, 1–18.

Handojo, A., Zahi, Y.M., Frankel, G. & Pascall, M.A. (2009). Measurement of adhesion strengths between various milk products on glass surfaces using contact angle measurements and atomic force microscopy. *Journal of Food Engineering*, 92, 305–311.

Jurado Alameda, E., Bravo Rodriguez, V., Altman Vaz, D. & de Cassia Siqueira Curto Valle, R. (2011). Effectiveness of starch removal in a Bath-Substrate-Flow (BSF) device using surfactants and \(\alpha\)-amylase. *Food Hydrocolloids*, 25, 647–653.

Jurado Alameda, E., Altman Vaz, D., Garcia Román, M. & Jiménez-Pérez, J.L. (2014). Study of heat-denatured whey protein removal from stainless steel surfaces in clean-in-place systems. *International Dairy Journal*, 38, 195–198.

Jurado Alameda, E., Herrera Márquez, O., Martínez Gallegos, J.F. & Vicaria, J.M. (2015). Starch-soiled stainless steel cleaning using surfactants and \(\alpha\)-amylase. *Journal of Food Engineering*, 160, 56–64.

Keidel, M., Bugiel, H., Miller, R. & Cerny, G. (2005). Abhärzeverhal-ten von Haferflockenanschmutzungen unter dem Einfluss verschiedener Reinigerkomponenten. *SÖFW Journal*, 131, 46–51.

Kim, J. & Digiano, F.A. (2009). Fouling models for low-pressure membrane systems. *Separation and Purification Technology*, 68, 293–304.

Krulis, M. & Rohm, H. (2004). Adaption of a vane tool for the viscosity determination of flavoured yoghurt. *European Food Research and Technology*, 218, 598–601.

Leach, H.W., McCowen, L.D. & Schoch, T.J. (1959). Structure of the starch granule. I. Solving and solubility patterns of various starches. *Cereal Chemistry*, 36, 534–544.

Lopez, O.V., Zaritzyk, N.E. & García, M.A. (2010). Physicochemical characterization of chemically modified corn starches related to rheological behavior, retrogradation and film forming capacity. *Journal of Food Engineering*, 100, 160–168.

Mc Clery, B.V., Gibson, T.S. & Mugford, D.C. (1997). Measurement of total starch in cereals products by amyloglucosidase- \(\alpha\)- amylase method: collaborative study. *Journal of the AOAC International*, 80, 571–579.

Miller, G.L. (1959). Use of dinitrosalicylic acid reagent for determination of reducing sugar. *Analytical Chemistry*, 31, 426–428.

Mukerjea, R., Slocum, G. & Robyt, J.F. (2007). Determination of the maximum water solubility of eight native starches and the solu- bility of their acidic-methanol and -ethanol modified analogues. *Carbohydrate Research*, 342, 103–110.

Olsen, H.S. & Falholt, P. (1998). The role of enzymes in modern detergency. *Journal of Surfactants and Detergents*, 1, 555–567.

Otto, C., Zahn, S., Rost, F., Zahn, P., Jaros, D. & Rohm, H. (2011). Physical methods for cleaning and disinfections of surfaces. *Food Engineering Reviews*, 3, 171–188.

Otto, C., Zahn, S., Plenker, J. & Rohm, H. (2014). Application of a flow cell for the comparative investigation of the cleaning behavior of starch and protein. *Journal of Food Engineering*, 131, 1–6.

Otto, C., Zahn, S., Hauschild, M., Babick, F. & Rohm, H. (2016). Comparative cleaning tests with modified protein and starch resi- dues. *Journal of Food Engineering*, 178, 145–150.
Prochaska, K., Kędziora, P., Thanh, J.L. & Lewandowicz, G. (2007). Surface activity of commercial food grade modified starches. *Colloids and Surfaces B: 60*, 187–194.

Rodríguez, M., Osés, J., Ziani, K. & Maté, J.I. (2006). Combined effect of plasticizers and surfactants on the physical properties of starch based edible films. *Food Research International, 39*, 840–846.

Saikhwan, P., Geddert, T., Augustin, W., Scholl, S., Paterson, W.R. & Wilson, D.I. (2006). Effect of surface treatment on cleaning of a model food soil. *Surface Coating Technology, 201*, 943–951.

Sorba, A. & Sopade, P.A. (2013). Changes in rapid visco-analysis (RVA) viscosity reveal starch digestion behaviours. *Starch/Stärke, 65*, 437–442.

Sun, J., Zhao, R., Zeng, J., Li, G. & Li, X. (2010). Characterization of dextrins with different dextrose equivalents. *Molecules, 15*, 5162–5173.

Tanaka, A. & Hoshino, E. (1999). Study on the substrate specificity of α-amylases that contribute to soil removal in detergents. *Journal of Surfactants and Detergents, 2*, 193–199.

Toure, Y., Rouxhet, P.G., Dupont-Gillain, C.C. & Sindic, M. (2011). Influence of soluble polysaccharide on the adherence of particulate soils. In: *Proceedings of International Conference on Heat Exchanger Fouling and Cleaning* (edited by M.R. Malayeri, H. Müller-Steinhagen & A.P. Watkinson). Pp. 219–226. Crete Island, Greece.

Uthumporn, U., Zaidul, I.S.M. & Karim, A.A. (2010). Hydrolysis of granular starch at sub-gelatinization temperature using a mixture of amylolytic enzymes. *Food and Bioproducts Processing, 88*, 47–54.

Visser, J. (1995). Particle adhesion and removal: a review. *Particulate Science and Technology, 13*, 169–196.

Wallhäußler, E., Hussein, M.A. & Becker, T. (2012). Detection methods of fouling in heat exchangers in the food industry. *Food Control, 27*, 1–10.

Zahn, S., Wehner, A. & Rohm, H. (2012). Influence of the type of gelatinized starch on the soiling of stainless steel. *Journal of Food Engineering, 111*, 186–189.

**Supporting Information**

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Photograph of the flow cell used in the cleaning experiments.