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Model food soils for investigating cleaning: A review

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ABSTRACT

Cleaning operations are performed regularly throughout the food industry. This review focuses on the removal of strongly adherent fouling deposits which compromise the performance and hygienic status of equipment and processes. Identifying and understanding the key mechanisms involved in cleaning food deposits is essential for selecting and optimising cleaning protocols. The complexity of these materials has prompted the use of model soil-surface systems for experimental investigations of cleaning. The factors that need to be considered in selecting model soil systems, the techniques used to measure and characterise cleaning, and the formulations that have been used to model food fouling deposits are discussed. Particular focus is given to deposits formed from liquid foods high in protein, starch, sugar and lipids. Biofilms, fouling layers generated in membrane operations and corrosion fouling are not considered.

Contents

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1. Introduction

Cleaning is a universal activity which is performed regularly in the food industry to prepare food items and products for sale *e.g.* vegetables, fruit, salads (Cunault et al. 2015) as well as to restore the surfaces of processing equipment to a clean state. This review focuses on the latter, and on foods which are processed in a fluid state (liquids, suspensions, emulsions *etc.*). The material to be removed, which we label the *soil*, may be:

(a) Fouling layers or other deposits generated on the surface, under the conditions used in processing. These include thermal fouling deposits generated from surface reactions or deposition on heated or cooled surfaces, and components present in the process stream which preferentially adsorb or attach to process surfaces.
(b) Residual material remaining after processing a previous product, which needs to be removed in order to avoid contamination of a subsequent product, as arises in multi-product lines. In this case the soil's properties are likely to be similar to the bulk product.
(c) Biofilms or other micro-organisms which attach to the surface and can contaminate the product by releasing unwanted substances, spores or other colonizing entities, promote corrosion, and compromise the hygienic status of the equipment.
(d) Corrosion products, generated by reaction between the food (or cleaning agent), the material of the surface and features such as seals and lubricants. In the food sector, material selection (EHEDG, 2005) aims to avoid this where possible.

This review focuses on type (*a*) soils, which are frequently difficult to remove as they have developed enhanced adhesion to the surface compared to the process stream. Their properties are derived from the material in the process stream, often as a result of ageing processes (Ali et al. 2015b), and are therefore difficult to predict and need to be measured *in situ*. Wilson (2018) identified two classes of soil layers playing an important role in the food sector: those principally generated by heat transfer (heating, cooling and freezing operations) and those generated by mass transfer, particularly in membrane separations; the latter not considered here.

Understanding cleaning and identifying cleaning mechanisms is important because cleaning operations take time, thereby reducing productivity, and consume large amounts of energy and cleaning agents. In the food sector, cleaning agents for wet processes are usually based on aqueous solutions, requiring clean water to prepare the solutions, chemicals to deliver the required functionality, and treatment processes to convert the spent cleaning solution to a form that is safe to discharge. For dry processes, both wet and dry cleaning methods are employed, with the choice determined by factors such as whether the dry contaminant is compatible with liquid cleaning agents, where removed soil may be relocated to, the scope for cross-contamination, and the ability to restore dry conditions. This review focuses on wet processes.

These aspects all impact the sustainability of cleaning operations, and can dominate the environmental footprint of food manufacturing processes (Tsai et al. 2021b; Gésan-Guiziou et al. 2019; Dvarionienė et al. 2012; Eide et al. 2003). Modern plants often employ cleaning-in-place (CIP) systems that recirculate flushing liquid, cleaning solutions, rinse water and sterilising solutions in sequence. In order to comply with hygienic design guidelines and maintain hygienic integrity, the units are not designed to be opened routinely for inspection or manual cleaning and the CIP protocol is based on validated programmes, assisted by sensors. Given the prevalence of liquid-based cleaning operations in the food sector, this paper focuses on soils for studying these applications.

The specification, design and development of such protocols requires an understanding of the mechanisms involved (Wilson, 2005). The variety of foods and processing techniques employed in the food sector means that there is a wide range of deposits and soils, and consequently a wide variation in observed cleaning behaviours. Fryer and Asteriadou (2009) classified cleaning operations in terms of liquid flow rates (relating to hydraulic forces imposed by the circulating fluid) and temperature as well as the type of cleaning solution (relating to aggressiveness of chemical action). They depicted this classification of soils according to their origin and cleaning requirements in a Cleaning Map (see Fig. 1). This allows an estimation of the effort required for soil removal. One drawback of this classification is that deposits exhibiting different cleaning behaviours can be grouped together, which can result in a loss of important information for the design of a cleaning processes.

In simple terms, cleaning requires the soil to be converted into a form which can be taken away from the surface by some combination of chemical action (promoting a change in its cohesion or adhesion) and hydraulic forces or mass transfer, both of which are enhanced by fluid velocity. The range of fluid mechanics phenomena involved in cleaning has been reviewed by Landel and Wilson (2021). They classified flows as either *confined*, as arises in piping and heat exchangers, and *free*

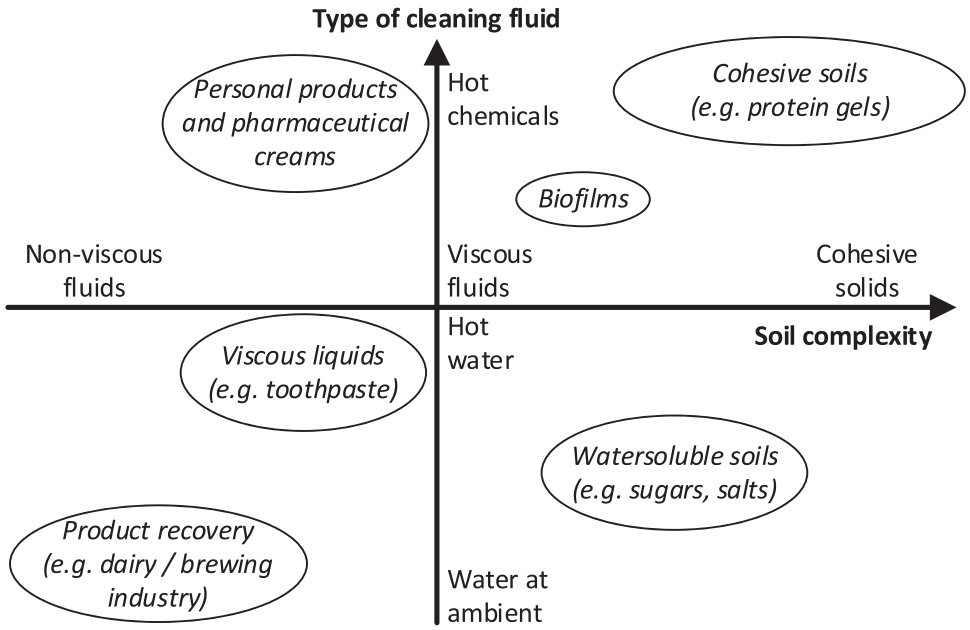


Fig. 1 – Cleaning Map
Adapted from Fryer and Asteriadou (2009).

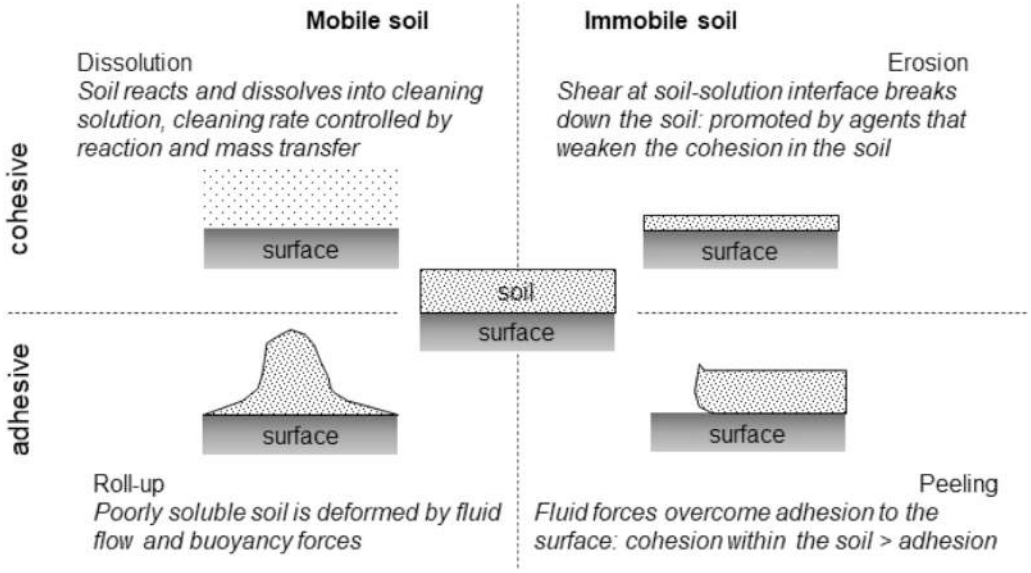


Fig. 2 – Soil removal modes in CIP processes involving flowing cleaning agents. Joppa et al. (2017b) presented a similar classification, labelling the modes as (clockwise order) 'diffusive dissolution'; 'cohesive separation'; 'adhesive detachment'; and 'viscous shifting'.

surface flows, such as those generated by jets and sprays. Bhagat et al. (2017) classified fluid driven removal mechanisms in terms of the mobility of the soil and the response to the imposed force, illustrated in Fig. 2.

The removal behaviour of residual product layers (*i.e.* case (b)) in CIP operations can in many cases be estimated by multiphase flow simulations if the properties of the soil remain similar to the raw material, or the effect of interactions with the cleaning agent can be quantified. The purpose of the cleaning agent is often to change these interactions, introducing reaction timescales to the problem. Experimental data are then needed to establish the sequence of events and dynamics. A further level of complexity arises when studying thermal fouling layers, as their thermal history means that their properties differ from the original material, and are subject to variation across a layer. For example, the soil next to the surface will have experienced the surface temperature for an extended period and any temperature-induced change will be greatest there. These factors render the identification of the mechanisms involved and quantifying the behaviour challenging. Studying cleaning is therefore inherently complex as the layer to be cleaned is often multiphase, heterogeneous, and features a range of properties resulting from the difference in history with location.

A major challenge in studying cleaning is preparing the layer to be cleaned. Layers need to be prepared reproducibly, ideally with known properties, in order to support systematic study. This has led to the use of model soils in experimental studies replicating the key features of the real layer, in order to elucidate the role of different factors and thereby guide the design and modelling of cleaning operations. In this review

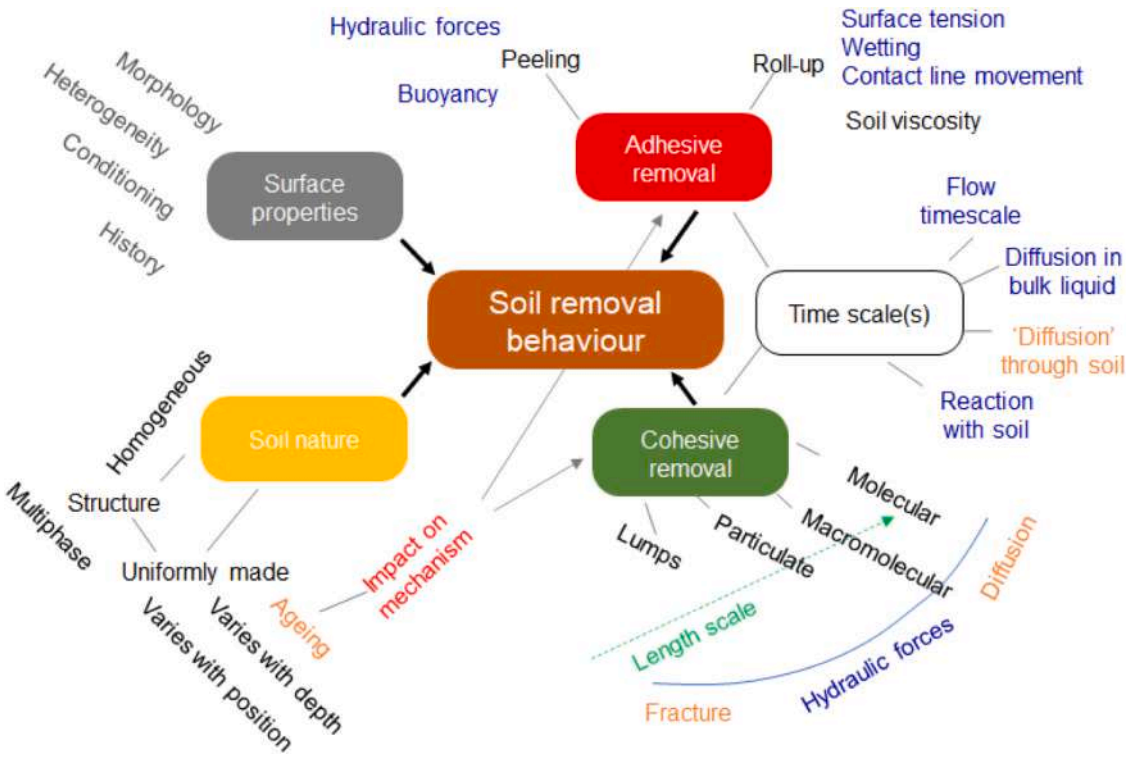


Fig. 3 – 'Mind map' of soil characteristics affecting removal behaviour. Blue text indicates factors controlled chiefly by cleaning agent nature and application. Orange text indicates changes determined chiefly by soil.

membrane soiling layers are *not* considered as these normally do not undergo extensive change after deposition, and the use of flat cell membranes allows uniform soil layers to be obtained relatively readily.

A wide range of materials has been used in model soil studies. The aim of this review is to catalogue and compare the merits of different model soils, to identify good practice and assist researchers in selecting potential candidates for future cleaning investigations. For this reason the next sections of this review focus on general considerations for soil (and soil-surface) selection, different soiling methods as well as monitoring and testing methods for food soils. The second part gives an overview of model food soils used for cleaning investigations reported in the open literature, with short summaries of the experiments and main findings. These sections are ordered in terms of the main component of the soil system, *e.g.* high-protein, high-carbohydrate, high-lipid and composite model systems. Section 9 focuses on non-food systems which have been used to model food soils. The final Section presents general guidance on soil-surface system selection. This review differs from the more general review of soil model systems by Toure et al. (2013) by focusing specifically on food soils, on experimental techniques, and on classifying soils according to their composition rather than fouling mechanisms.

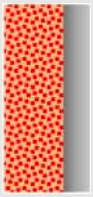
2. Considerations for soil selection and adaptation

The first step, before starting cleaning experiments, is to identify a suitable soil-surface system. The suitability of different soil-surface systems depends on the scientific question being addressed. This means that the objective of the investigation needs to be defined accurately. Moreover, transfer of the experimental results depends on the similarity between the properties of the model and real systems in terms of structure and composition as well as thermal and chemical reaction. In order to compare different experiments and evaluate the influence of cleaning parameters the model soil-surface system needs to meet several requirements, which are discussed in the next section.

In addition to the soil and surface properties, there are further characteristics concerning time and length scales to consider when choosing an appropriate soil system. An overview of the factors and properties influencing soil removal behaviour is given in Fig. 3. Having established the known or expected removal behaviour, experiments can then be designed accordingly. The nature and properties of the surface and those of the soil determine their interactions and hence the mechanisms involved in removal: in the Figure the latter are classified broadly as adhesive or cohesive mechanisms (see Fig. 2). The structure of the soil and how its components interact with the cleaning agents and/or forces imposed on it determine the cleaning action and the timescales. It is important that any model system replicates the primary mechanism active in the system of interest. The range of phenomena involved is very large, as reported by Landel and Wilson (2021), and it is important to ensure that simplifications introduced do not change the mechanism.

From this point on we use the term 'soil' to refer to the soil-surface system of interest. The influence of the properties of the surface (both topological and chemical) on adhesion and removal mechanisms relying on adhesive breakdown at the substrate-soil layer interface may be readily understood, such as promoting dewetting and roll-up, slip, and displacement as a result of changes in charge. They can also affect the characteristics of a soil layer *via* control of heat transfer during its formation, preferential attachment of species at the interface which promote

Table 1 – Grades of soil complexity.

	'Ideal'	'Model'	'Standard'	'Real'
Schematic				
Reproducibility	Very good	Good, to allow series of tests	Good, to allow benchmarking	Poor, variable conditions
Material complexity	Usually low to support detailed models	Simplified to capture key parts	Complex, but uniform	Very complex and variable
Transferability of findings to practice	Low: influence of other factors has to be established	Medium: key findings establish trends	Good: but limited to closely related systems	Good when variability is low
Scientific complexity	Detailed and rigorous	Compromise, based on key mechanisms	Empirical, based on general trends	Empirical
Quantitative understanding	Full	Reduced order models	Empirical	Empirical

subsequent growth at the macroscale (conditioning), and mechanical effects arising from structuring of the substrate. There is a substantial body of experimental work seeking to isolate substrate chemistry and substrate shape on deposition behaviour in biofilms, crystallisation fouling, and reaction fouling, *e.g.* Schnöing et al. (2020) and Saget et al. (2021).

Given the complexity involved in the preparation stage (such as generating a fouling deposit) it is difficult to separate surface shape and surface composition effects on removal behaviour – particularly for the multi-component mixtures employed in food applications - so the majority of studies on model soil-surface systems have employed substrates similar to those employed in industry, accompanied by full characterisation of the surfaces, to reduce the complexity in transferring results into practice.

2.1. *Essential requirements for model soil layers*

For systematic investigation of cleaning processes, model soils are usually used rather than samples of fouling layers from process plants. The reasons for this is the need to achieve reproducible cleaning results and thus allow the influence of selected factors to be determined. This imposes the following requirements on the soil:

(a) Reproducibility of chemical composition;
(b) Reproducibility of the internal structure (which may not be homogeneous);
(c) Reproducibility of layer thickness (*i.e.* spatial uniformity);
(d) Stability over the desired time scale;
(e) Sufficient resistance to the cleaning process (in order to be able to determine the progress of cleaning experimentally in a time-resolved manner).

Further specifications for the soil layer properties are set by the nature of the experimental system and the measuring techniques to be used. Regarding the latter, the universally important question is 'How clean is clean?', *i.e.* the extent of removal to be achieved in practice. The answer can range from restoration of operating efficiency (*e.g.* performance restored within desirable ranges) to complete decontamination (no measurable levels within detection limits) or disinfection (more common in food applications, relating to inactivation of any microbial species present, not necessarily requiring their removal). This is a universal question for all cleaning operations see Wilson et al. (2022) and the answer is determined in practice by the risk associated with a given amount of soil remaining on the surface. Studying decontamination and disinfection requires ready access to a surface and a reliable measurement technique, and soils suitable for studying process-performance cleaning are not necessarily suitable for investigating decontamination. For example, Schöler et al. (2012) monitored the removal of starch-based soils by adding zinc sulphide particles (of order 20 µm) to render the layers phosphorescent under UV illumination. Dark regions indicated the absence of particles but not decontamination at smaller length scales.

Other properties of the model soil which are not mandatory but can ease handling before and during experiments include:

(a) Stability for at least a short storage time under defined conditions.

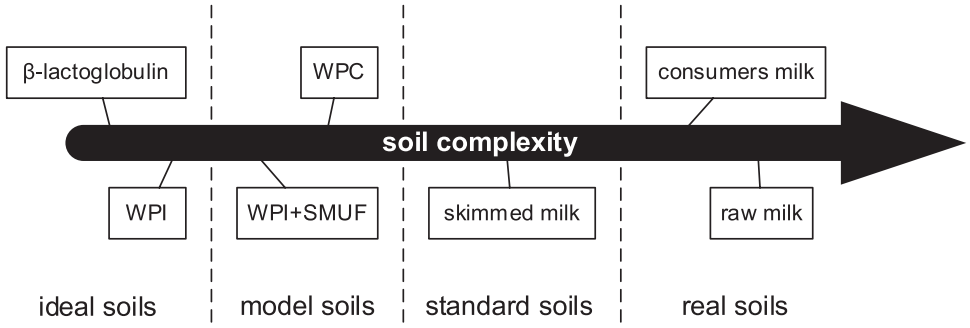


Fig. 4 – Examples of soils used for cleaning investigations in the field of cow's milk fouling. WPI – whey protein isolate solution; WPC – whey protein concentrate solution; SMUF – simulated milk ultrafiltrate.

(b) Ingredients are readily available, non-toxic, affordable and require simple storage.
(c) Soil preparation is not too complex and can be done by different people without expert training.
(d) Soil preparation is not too time consuming.

2.2. *Complexity of soil systems*

A large number of cleaning studies using different food soil systems can be found in the literature. Some are far from real soils, such as polystyrene beads used as model for particulate deposits (Beck et al. 2005; Bobe, 2008), while others contain many ingredients and are therefore very complex, *e.g.* the baked blend of pasta, milk, cheese and margarine studied by Cuckston et al. (2019): formulations with intermediate complexity are used as well.

Real soils generated by fouling or other deposition processes are in most cases neither homogeneous nor reproducible. It is therefore not appropriate to use those soils for fundamental cleaning investigations. However, it may be necessary to use such soils in cleaning experiments to support transfer of knowledge of cleaning mechanisms from model soils to "real life" and to optimize cleaning procedures on process plants. Examples include raw milk fouling layers, *e.g.* Timperley and Smeulders (1988), dried blancmange soils (Köhler et al. 2016), and mustard layers (Jensen et al. 2007).

In some cases, standard soils are preferred to real soils. These are simplified versions of a real soil, with set composition and produced under well-defined conditions, so that the results can be transferred to operating practice readily. Standard soils can be produced reproducibly but are still complex. They usually consist of several different ingredients and the interactions between these are not necessarily understood. Extrapolating cleaning results obtained with standard soils to new equipment designs is therefore not straightforward, as is deciphering the observed performance in terms of cleaning mechanisms. Nevertheless, they are well-suited for comparing chemical formulations, developing cleaning protocols and validation programmes, as well as testing new soil testing methods. An example is the suite of standard soils for dishwasher testing in DIN EN 60436, featuring soils based on spinach, minced meat and porridge. These imitate the deposits on dishes and flatware found in households. Being applied by a pastry brush, they are very inhomogeneous in terms of thickness and this aspect can restrict their usefulness for mechanistic insight and knowledge of fundamental cleaning mechanisms.

Model soils featuring lower complexity are often used for cleaning investigations. With good reproducibility and sufficient knowledge of chemical composition, these allow investigation of interactions between the soil and cleaning agent, especially in terms of chemical reaction and mass transport mechanisms. Examples are dried starch layers, *e.g.* Augustin et al. (2010), and whey protein fouling deposits, *e.g.* Saikhwan et al. (2010).

Table 2 – Examples of soil layer preparation methods.

Method Ingredient	Pipetting	Scraping / Coating with knife / blade	Dipping	Spraying	Spin coating	Sedimentation	Circulating / Fouling
High-protein	Gelatine BSA						Milk Whey protein Egg white Soy protein
High-carbohydrate	Starch Honey	Starch Tomato paste	Starch	Starch Xanthan gum	Agarose		Xanthan gum Glucose syrup
High-lipid	Lard	Lard Butter Petroleum jelly Egg yolk	Lard	Sunflower oil Lipid nanoparticles Mineral oil Egg yolk			Mayonnaise Lipid nanoparticles Coconut milk
Composite		Bread dough Mustard Custard					Custard
Non-food	PVOH	Paraffin Petroleum jelly		Glycerine		Polystyrene	

Ideal soils have low complexity and usually consist only of few ingredients, with known chemical composition. They are used to gain quantitative insight into fundamental mechanisms and processes. Cleaning results can be used to develop detailed models but their application to practical cases need estimation of other present components influence. An example of an ideal soil is a denatured β-lactoglobulin layer such as that used by Saikhwan et al. (2010) to gain insight into the cleaning of cow's milk deposits. The advantages and disadvantages of the different grades of soil complexity are summarized in Table 1.

An unambiguous assignment of all the different model soils to these four classifications is not possible. Most of the non-food model systems presented in Section 9 can be described as 'Ideal' whereas the composite and other soil systems in Section 8 are almost exclusively 'Real'. The differentiation between 'Model' and 'Standard' complexity is not well-defined and will depend on the application.

Soils for cleaning investigations should be as simple as possible and only as complex as needed to answer the specific scientific question. Soils with different grades of complexity are needed to translate fundamental insight into practice reliably, and for each investigation a soil system with the right grade of complexity has to be selected. Fig. 4 shows the range of formulations which have been employed to understand the cleaning of cow's milk fouling deposits.

Milk is a complex food mixture. One of the most simple model milk soils is a solution of β-lactoglobulin, one of the whey proteins present in milk which is found in large amounts in Type A (formed at moderate temperature) fouling deposits (Lalande and Tissier, 1985). The deposits generated are therefore different from those found in milk processing but especially for understanding reactions between cleaning agents and milk fouling experiments with β-lactoglobulin are necessary. If whey protein isolate (WPI) is used instead, the different salt contents result in different microstructures (stranded *vs*. particulate gels) and the model soils exhibit differences, *e.g.* in their swelling behaviour (Saikhwan et al. 2010). The next step towards real soils could be to add the salts usually present in cow's milk (present also in SMUF, simulated milk ultrafiltrate). Boxler et al. (2013) used this model system for example to evaluate the benefits of a surface coating on milk fouling cleaning. This combination still lacks several important ingredients of cow's milk, such as the casein protein fraction, lactose (milk sugar) and milk fats.

A low amount of fat and lactose in the model soil can be obtained by using whey protein concentrate (WPC) solutions for soil production (Saikhwan et al. 2010). WPC is usually produced by drying whey, which is a residual product from cheese production. The lactose content (up to 50% of the dry weight), and also the fat content of WPC, can vary as a result of different pre-treatments. Hence, the whey protein content of WPC powder ranges from 34% to 80% and thus enables further approximation to real milk soils (Guo, 2019).

If caseins are to be considered, skimmed milk can be used to produce the model soil. Skimmed milk contains all components of cow's milk in their normal concentrations apart from its reduced fat content and is produced by centrifugation of raw milk to separate cream. This process is also commonly used in the production of consumer milk (pasteurized or ultra-heat-treated, UHT) to adjust the fat content. Fan et al. (2015) used skimmed milk for investigating the influence of the pre-rinsing step. In order to deduce advises for milk industry directly, a model with similar swelling behaviour to real milk fouling was used. Consumer (retail) milk can be used for soil production but this will differ from raw milk owing to the denaturation of the milk proteins induced by any thermal pasteurisation steps in milk production. The proteins then behave differently and the fouling layers are different, which in turn influences their cleaning behaviour (Christian et al. 2002; Magens et al. 2019; Liu et al. 2020). As a result the cleaning of raw milk deposits has been investigated by several groups, including Timperley and Smeulders (1988), Goederen et al. (1989) and Yang et al. (1991). Seasonal variation in milk properties needs to be monitored and accounted for. Raw milk has been used less often in recent studies of cleaning in the academic literature.

3. Soiling methods

Due to the requirements listed above, a model system with defined chemical composition is usually used for the production of the soil layers, *e.g.* by using powders that are dispersed in the solvent (usually water) in a defined concentration. The production of soil layers involves a set protocol, divided into a large number of individual steps with defined conditions (such as temperature, duration, stirrer speed, humidity, *etc.*). This is necessary to ensure good reproducibility of the soil and minimize differences between test samples from different batches.

The application of the soil can be realized in different ways. More frequently used methods are spraying (Pérez-Mohedano et al. 2016; Joppa et al. 2017b), spreading (Köhler et al. 2021), scraping (Föste et al. 2014) and pipetting (Saikhwan et al. 2010), as well as fouling on heated test section(s) in a batch process (Boxler et al. 2013) or flow channel (Bode et al. 2007). The application method to be used depends on the viscosity of the soil material, the surface to be soiled and the desired thickness of the soil layer. Examples of model soils applied by the different soiling methods are given in Table 2.

Pipetting is a simple method suited for application of low viscosity fluids. The quantity of soil material can be easily and precisely defined by the volume. Spraying can also be used for inviscid soil materials. The soil layer can take the form of droplets or films, depending on the wettability of the substrate and the amount of material applied. Spin coating can be used to generate particularly uniform layers, for moderately viscous materials. An aliquot of soil material is placed on the substrate and is spread uniformly by the rotation of the substrate. Excess material is spun off the substrate and reproducible, thin layer thicknesses can be achieved.

These methods are not suitable for viscous and soft solid soil materials, as uniform application cannot be ensured. For viscous soil material scraping with a knife, scraper or blade is more appropriate. The most important requirement for scraping methods is a reproducible thickness, usually ensured by using a well-defined gap between surface and scraper. The velocity (and any fluctuation thereof) of the scraper movement can affect the soil layer thickness and properties. As a result some groups have developed automated systems for scraping using motors or weights, *e.g.* Schöler (2011).

In some cases, dipping the substrate into the soil material can be used for soil application. The main problem here is to obtain a reproducible amount of soil on the substrate.

Table 3 – Overview on frequently used soil monitoring and testing methods.

Attribute	Technique	In-situ	Ex-situ	Wet	Real-time	Local (L) Overall (O) Scan (S)	Principle and Requirements	Reference (s)
Amount or coverage	Gravimetric/ Volume displaced		y			O	Sample has to stay attached to the test section.	Boulangé-Petermann et al. (2006);Wilson et al. (2015);Otto et al. (2016);Fuchs et al. (2017);Vicaria et al. (2018a)
	Quartz crystal microbalance	y		y	y	O	Monitor oscillation of crystal. Small amounts and slow flows. Temperatures up to 65 °C.	Avila-Sierra et al. (2021);Kanasaki et al. (2016);Yang et al. (2018);Murcek et al. (2021)
	Optical microscopy		y			L, O	Determination of surface coverage from microscopic images.	Detry et al. (2007);Schoenitz et al. (2014);Rodgers et al. (2019)
	Ellipsometry	y	y	y	y	L, S	Measures changes in polarisation in very thin films. Requires transparent solutions or substrates for light path, knowledge of refractive indices.	Day et al. (2010);Santos et al. (2003)
	Magnetic resonance imaging	y	y	y	y	L, S	Excitation of magnetic spins. Requires non-ferrous materials and surfaces: sample has to fit inside magnet coil.	Vrouwenvelder et al. (2009);Creber et al. (2010a; 2010b);Yan et al. (2021)
	Phosphorescence and fluorescence (quantitative)	y	y	y	y	L, S	Emission of light at specific wavelengths. Calibration required. Avoid saturation. In some cases, adding ZnS crystals to soil matrix is necessary.	Schöler et al. (2009; 2012);Augustin et al. (2010);Mauermann et al. (2012);Föste et al. (2014);Gordon et al. (2014);Helbig et al. (2015);Fuchs et al. (2017);Joppa et al. (2017a, 2017b; 2019)
	Fluorescence (qualitative), *e.g.* rhodamine/UV	y	y	y	y	L, S	Emission of light at specific wavelengths. Care in applying dye. Removal affected by drying out.	Beck et al. (2005);Bobe et al. (2007);Gerhards and Schmid (2013);Wilson et al. (2015)
Thickness	Optical microscopy	y	y	y	y	L, S, O	Reflection or transmission of light. Either solvent or substrate has to be transparent or only ex-situ measurement possible.	Spiegel et al. (2022)
	Confocal microscopy	y		y	y	L, S	Programmed focus of light/laser beams in 3-D. Either solution or substrate has to be transparent.	Möhle et al. (2007)
	Confocal LED sensor	y	y	y	y	L, S	Location of interface by reflection of different light wavelengths. Wet testing requires solution transparent to light.	Cuckston et al. (2022)
	Electron microscopy (including ESEM)		y	ESEM		L, S	Various methods involving focus of electron beam. Sample may need conductive coating. Sample has to withstand vacuum or reduced pressure.	Roever, de, Huisman (2007);Tan et al. (2014);Olufade and Simonson (2018)
	Magnetic resonance imaging	y	y	y	y	L, S	As above. Strong fields may be required to measure deposit thickness	Schork et al. (2019; 2021)
	Fluid dynamic gauging (FDG)	y	y	y	y	L, S	Pressure drop-flow relationship controlled by distance from nozzle. FDG nozzle has to inject or withdraw liquid. Soil surface has to be rigid over timescale of experiments.	Tuladhar et al. (2000);Gordon et al. (2010a; 2014);Yang et al. (2014);Föste et al. (2014);Ali et al. (2015a);Saikhwan et al. (2015);Schoenitz et al. (2015);Tsai et al. (2021a)
	Contact probe (mechanical, electrical)	y	y	y	y	O, S		Diehl et al. (1990);Gale and Griffiths (1995)

(continued on next page)

– Table 3 (*Continued*)

Attribute	Technique	In-situ	Ex-situ	Wet	Real-time	Local (L) Overall (O) Scan (S)	Principle and Requirements	Reference (s)
							Precision movement of probe. Soil properties have to differ from solution. Surface has to resist intrusion by the probe.	
	Mechatronic Surface Sensor (MSS)		y	y	y	L	Vibration change of surface waves. The amplitude is related to the soil thickness, the damping factor to the elasticity.	Pereira et al. (2006)
	Ultrasound	y	y	y	y	L, S	Reflection and attenuation of ultrasound waves. Calibration often required even when properties of soil layer are known.	Withers (1994);Lucas et al. (2017);Simeone et al. (2016);Escrig et al. (2019)
	Static multiple light scattering	y		y	y	O	Thickness calculation from transmission and backscattering signals.	Hofmann (2007);Helbig et al. (2019)
	Thermal resistance (steady or transient)	y	y	y	y	L	Presence of deposit layer inferred from changes in heat flux or temperature decay	Davies et al. (1997);Bouvier et al. (2020)
Composition – chemical	Magnetic resonance imaging	y	y	y	y	L, S	As above. Different excitation frequencies can probe presence of different species	Schork et al. (2019)
	Confocal microscopy, including CARS	y	y	y	y	L, S	Species excited at the laser wavelength: calibration needed. Not suitable for solutions opaque to lasers.	Xu et al. (2018)
	ATR FTIR		y			L, S	IR peak for the substrate does not overlap with the solvent.	Pousti et al. (2018)
	Atomic force microscopy, AFM					L, S	Interaction of probe with surface, different modes of action. Nature of surface material (elastic, viscous) identified from tapping response.	Detry et al. (2011)
	X-ray photoelectron spectroscopy		y			L	Elemental composition determined by detection of electrons emitted after irradiation the soil with X-rays.	Boyd et al. (2001);Detry et al. (2011)
	Chemical/physical assays – overall change	y	y	y	y	O	Measure change in composition of cleaning solution to material released from soil.	Siegmann-Hegerfeld et al. (2013);Jurado-Alameda et al. (2011a; 2011b; 2015; 2016);Herrera-Márquez et al. (2019);Vicaria et al. (2017)
Composition - Structural	Magnetic resonance imaging	y	y	y	y	L, S	Differences in T_1 and T_2 time constants can identify voids, solid region. Requirements as above. Materials need suitable T_1 and T_2 values.	Ling et al. (2014);Schopf et al. (2020)
	Photography/ Microscopy of surface properties		y			L, S	Photographs or microscopic images can be used to obtain information on homogeneity and roughness of soils.	Cuckston et al. (2019)
	Laser diffraction	y	y	y	y	O	Size measurement of removed particles and soil fragments in order to determine removal mechanism.	Sauk et al. (2018);Gottschalk et al. (2019)
Mechanical properties	QCM	y		y	y	O	Principle described above. Thin layers – elastic or viscoelastic behaviour	Akhtar et al. (2010)
	FDG	y	y	y	y	L, S		

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– Table 3 (*Continued*)

Attribute	Technique	In-situ	Ex-situ	Wet	Real-time	Local (L) Overall (O) Scan (S)	Principle and Requirements	Reference (s)
							Principle described above. Strength inferred from deformation observed or not when given flow stress imposed.	Tuladhar et al. (2000);Chew et al. (2004);Saikhwan et al. (2006);Yang et al. (2014);Saikhwan et al. (2015)
	Rheometer		y	y		O	Flow property measurement of wet or liquid soils.	Goode et al. (2010);Helbig et al. (2019)
	AFM		y	y		L, S	Principle described above. Mechanical properties of thin (nano-metre) layers.	Goode et al. (2013);Benoit and Selhuber-Unkel (2011)
	SEM-force probe		y		y	L	Micromanipulator with force microtransducer deforms features on surface. Adhesion of crystals and cells.	Ferrell et al. (2011)
	Micromanipulation	y	y	y	y	O, L	Arm or blade moved through soil layer and force measured, giving adhesion and cohesive response of thin layers. Best suited for flat surfaces.	Liu et al. (2002; 2006b; 2006c; 2007);Liu et al. (2020);Akhtar et al. (2010);Herrera-Márquez et al. (2020)
	Millimanipulation	y	y	y	y	O	Similar to micromanipulation. When sample is immersed in cleaning solution, evolution of properties can be monitored.	Ali et al. (2015b);Magens et al. (2017);Cuckston et al. (2019);Helbig et al. (2019)
	Texture analyser ®		y	y		O	Contact probe imposes strain on material and force response measured.	Föste et al. (2014)
Thermal properties	Heat flux sensors with FDG	y		y	y	L	Combination of thickness and thermal resistance measurement yields thermal resistance and conductivity. Requires flat test surfaces, access for FDG and heat flux sensor.	Davies et al. 1997;Tuladhar et al. (2002b)
	DSC/DMA		y	y		O	Energy and mechanical response to temperature profile measured. Usually requires transfer of sample from native surface.	Otto et al. (2016);Helbig et al. (2019)

Table 4 – Overview of model systems for Type A milk fouling deposits, ordered as in the text.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Milk	Milk with radioactive labelled milk	Dry milk film on SS disks Ø 37 mm	Steam heating until dry	Milk cooked on a disc	Soil remaining with time at different alkali concentrations	0.04–0.6 wt % NaOH	Radioactivity	Determination that the soil removal is first order with the alkali concentration	Jennings (1959)
Skim milk	Skim milk with 3.5 wt% protein	Mineral rich (~70 wt% calcium phosphate) deposit with only 11 wt% milk proteins on 316 SS coupons	UHT fouling (137 °C, 8 s) for 15 h	Milk fouling over a plate coupon	Structure and composition of cleaned deposits	1.5 wt% NaOH at 100 & 120 °C, 0.5 wt% HNO_3 at 80 °C	SEM, CLSM, EDX	Proposed model for alkaline and acid cleaning	Hagsten et al. (2019a)
Skim milk	As above	As above	As above	As above	$T_{cleaning}$ = 100–120 °C, v = 1.6–3 m/s	1.5–3 wt% NaOH	Photographs, and a laser triangulation sensor for thickness measurements	Alkaline degradation of the proteins necessary to remove the mineral deposit with the acid	Hagsten et al. (2019b)
Whole milk and whey	Whole milk, whey (5.7 wt% solids)	Milk and whey fouling deposit, from pasteurization and evaporation, on SS tubes or pipes	Pasteurization at 70 or 90 °C, and evaporation at 50–75 °C	Fouling in a four effect evaporator	Cleaning at 3000 L/h at 70 °C	1 wt% NaOH, 1 wt% HNO_3	Chemical oxygen demand (COD) and calcium content of the cleaning solution	High NaOH concentrations make a rubber-like layer difficult to remove	Jeurnink and Brinkman (1994)
Whey protein	WPC 35 wt%	Fouling deposit on 316 SS tubes Ø 6 mm	3.5 wt% ,72–86 °C and 0.8 L/min (Re = 4600) for 60 min run	Fouling in concentric tube heat exchanger	Thermal conductivity of deposits, cleaning temperature, Re = 500–5000	0.5 wt% NaOH	Bradford assay, heat flux sensor	Study of the three stages of cleaning, *e.g.* in the uniform stage temperature dependence of ~50 kJ/mol, and proportional to $Re^{0.2–0.25}$	Gillham et al. (1999)
Whey protein	WPC 35 wt%	Fouling deposit on 316 SS tubes Ø 6 mm	3 wt% , 75–95 °C	Fouling on a coupon	$T_{cleaning}$ = 30–70 °C, Re = 340–5140	0.5–2 wt% NaOH	Bradford assay	Observation of a constant dissolution rate, which decreases above 0.5 wt% NaOH, resulting in an optimum alkali concentration for protein cleaning	Bird and Fryer (1991)
Whey protein	WPC 80 wt%	Gel layer on steel surface on SS tube Ø 16 mm	25 wt% , 79.5 °C	Gelation within a rotating tube	$T_{cleaning}$ = 45–85 °C, v = 0.09–0.46 m/s	0.5 wt% NaOH	UV spectroscopy	Proposed a mass transfer-based model of cleaning	Xin et al. (2002b)
Whey protein	WPC 30 wt%	Fouling deposit and gelation on 316 SS plates 150 mm × 15 mm	As inTuladhar et al. (2002a) and Xin et al. (2002b)	Fouling or gelation in a stagnant plate	Soil preparation method	0.5 wt% NaOH	FDG	Soiling conditions, *e.g.* protein concentration, affect the deposit formed and thus the	Hooper et al. (2006b)

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– Table 4 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
								resulting cleaning process	
Whey protein	WPC 35 wt%	Fouling deposit on 316 SS plates 150 mm × 15 mm	3.5 wt% recirculating at 74 °C for 90 min	Fouling on a plate	$T_{cleaning}$ = 20–50 °C, υ = 0.03–0.3 m/s	0.3–2 wt% NaOH	FDG and Bradford assay	Thickness quantification of the swelling stage and the uniform removal stage	Tuladhar et al. (2002a)
Milk	Milk	Fouling deposit on SS disks Ø 50 mm		Fouling on a coupon	Additives: EDTA or hydrogen peroxide	0.5 wt% NaOH	Images	Development of empirical models	Dürr and Graßhoff (1999)
Whey protein	WPC 85 wt%	Semi-infinite gel in glass capsules Ø 12 mm, and fouling deposit on a heated SS rod Ø 17 mm	Gels at 14–26 wt% , 80 °C for 1 h, or 2–6 wt% WPC solutions recirculated at 81 °C	Gelation in a static tube and fouling over a cylindrical rod	Protein concentration of the hydrogel	0.5 wt% NaOH	UV spectroscopy, conductivity, turbidity, and temperature measurements for heat transfer coefficient calculations.	Marked effect of the protein concentration in cleaning using gels or fouling deposits	Fickak et al. (2011)
Whey protein	pure βLg	Semi-infinite gel in glass capsules Ø 11 mm	15 wt%	Gelation in a static tube	Concentration of salts in the cleaning solution (LiCl, NaCl, KCl, MgCl2, CaCl2)	0.23 wt% NaOH	UV spectroscopy	Added salts markedly reduce the extent of swelling and the dissolution rate	Mercadé-Prieto et al. (2007c)
Whey protein	WPC 80 wt%	Dry fouling deposit on SS scourer pieces Ø 20 mm	Immersion in 45 wt% , 121 °C for 1 h autoclaving + drying at 60 °C for 12 h	Dipping using a scourer	Investigate packed column with different cleaning agents	Different commercial surfactant solutions, proteases and NaOH solutions (0.05–1 wt%)	Weight measurements	Surfactants alone do not help detergency, NaOH needed for cleaning	Jurado-Alameda et al. (2014)
Whey protein	WPC 80 wt%	Semi-infinite gel in glass capsules Ø 5 mm	16.7 wt%, 80 °C for 20 min	Gelation in a static tube	NaOH diffusion in the gel; $T_{cleaning}$ = 20–60 °C, $T_{gelation}$ = 75–95 °C; gelation pH 7–13.8	NaOH up to 4 wt % (1 M)	UV spectroscopy	First determination of dissolution rates for long times; gel characteristics strongly determine dissolution rates	Mercadé-Prieto and Chen (2006)
Whey protein	Pure βLg, WPI, WPC 80 wt% and WPC 35 wt%	Thick gels	Equivalent βLg concentration of 14.6 wt%, 80 °C	Gelation in a Petri dish	Different whey protein powders	NaOH up to 4 wt % (1 M)	FDG	Marked swelling differences between stranded and particulate gels	Saikhwan et al. (2010)
Whey protein	WPI	Thick whey protein gels	15 wt%, 80 °C for 35 min	Gelation in a static tube	Shear modulus with gel depth during swelling and dissolution	NaOH up to 4 wt % (1 M)	Dynamic microindentation	First mechanical characterization of protein hydrogels	Hu et al. (2017)

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– Table 4 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
								undergoing swelling and dissolution	
Whey protein	WPI	Semi-infinite gel in glass cuvette 3.5 × 12.5 × 45 mm	12–20 wt%, 80 °C for 30 min	Gelation in a cuvette	Protein concentration within ~1 mm of the gel surface, at different dissolution times	0.12 wt% NaOH	Coherent Anti-Stokes Raman Spectroscopy (CARS)	Determination of steady state protein concentration in the swollen layer during dissolution	Xu et al. (2018)
Whey protein	WPI	Semi-infinite gel in plastic centrifuge tubes Ø 9 mm	15 wt%, 80 °C for 1 h	Gelation in a static tube	Gel microstructure and chemical interactions, by changing gelation pH 2–11	0.1, 0.5 and 4 wt % NaOH	UV spectroscopy, HPLC, mechanical testing	Identification that the main chemical interactions destroyed during dissolution are of hydrophobic nature	Fan et al. (2019b)
Whey protein	Pure βLg	Semi-infinite gel in glass capsules Ø 11 mm	15 wt%	Gelation in a static tube	Gelation conditions: $T_{gelation}$ = 65–90 °C, for 2–3600 min	NaOH up to 4 wt % (1 M)	UV spectroscopy, SDS-PAGE	Strong inverse correlation with the amount of proteins stabilized by non-covalent bonds and the dissolution rate in alkali	Mercadé-Prieto et al. (2006)
Whey protein	WPI	Soluble protein aggregates	5.5 wt%, 80 °C for 20 min	Soluble protein aggregates	Breakdown kinetics at different concentration of aggregates and NaOH concentration	0.5–4 wt% NaOH	HPLC	Alkaline breakdown kinetics slow down at high NaOH concentrations, explaining the existence of an optimum cleaning concentration	Fan et al. (2019a)
Whey protein	Pure βLg	Semi-infinite gel in glass cuvettes 3.5 × 12.5 × 45 mm	15 wt%	Gelation in a cuvette	Fluorescence intensity profiles of gels undergoing swelling and dissolution	NaOH up to 4 wt % (1 M)	Fluorescence microscopy	First confirmation of steady state conditions of the swollen layer during dissolution. Quantification of the protein content with NaOH very difficult	Liu et al. (2018)
Whey protein	WPC 35 wt%	Fouling deposit on SS disks Ø 20 mm	1.5 wt%, 54–130 °C	Fouling in a PHE	Variation of the chemical exposure	0.1–1 wt% NaOH	Heat transfer coefficient and pressure drop	Water rinsing can remove swollen deposit previously treated with alkali. Substantial alkali treatment necessary for complete removal	Christian and Fryer (2006)

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– Table 4 (Continued)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Whey protein	WPC 35 wt%	Fouling deposit on SS tube Ø 8 mm	3.5 wt% 90–110 °C	Fouling in an anular tube	Effect of pulsating cleaning flow	0.5 wt% NaOH	Heat transfer coefficient, Bradford assay	Improved cleaning with pulsed flows, particularly at higher maximum velocities and waviness	Bode et al. (2007)
Whey protein	WPC 75 wt% with added calcium	Fouling deposit on SS PHE plates 0.825 m^2	4.8 wt%, 60–95 °C	Fouling in a PHE	Effect of *Re* during fouling on subsequent cleaning	2 wt% NaOH	Pressure drop	Fouling deposits formed at low speeds Re = 2000) were easily removed, but those formed at high speeds Re = 5000) were not.	Khaldi et al. (2015)
Whey protein	WPC 35 wt%	Fouling deposit on SS disks Ø 26 mm	1.5 wt% at 9°C	Fouling on a coupon	Adhesive and cohesive strength of deposits under cleaning conditions	0.1–5 wt% NaOH	Pulling force	Adhesive strength is greater than cohesive strength, and depends on process variables	Liu et al. (2006a)

Dipping is often used if the inner surface of the substrate should be soiled as well, such as the stainless steel wads employed by Jurado-Alameda et al. (2015). Soil application by brushing is used for inhomogeneous standard soils featuring large pieces, like spinach or minced meat, with inherent disadvantages associated with the resulting inhomogeneity, variation in thickness and difficulty in applying a reproducibly amount of soil to the surfaces. Brushing can still be a useful application method for uneven substrates. Particulate soil layers can be produced by sedimentation from aqueous suspensions: it is used for non-food soils imitating spores or yeast cells and is prone to give uneven soil layers.

Another approach used to produce soil layers for cleaning investigations is to circulate the soil material through a flow channel in which the substrate forms part of the channel wall. For some soil materials, the surface needs to be heated or cooled in order to promote deposition: the system then mimics a fouling system. Heated or cooled test sections positioned in batch tanks are also used. While reproducing the conditions involved in heat exchanger fouling to some extent, thermal fouling preparation methods are difficult to control in terms of reproducible mass, thickness, composition and uniformity.

After creating the soil layer a conditioning step is often needed to generate the desired soil properties. Heating to achieve denaturation of proteins is frequently used (with dairy soils, often > 70 °C for a set time period). Thermal fouling preparation methods do this in a single step: for others, oven-based methods are common with both closed and open configurations. For the latter, drying needs to be controlled or even avoided as it can create a surface crust which increases the resistance to cleaning. When used, drying needs to be conducted to a reproducible final moisture content.

4. Methods for soil layer detection, monitoring and characterization

The simplest measure is the amount of soil present on the surface. Methods to determine the presence or absence of soiling material on a surface, such as 'cleanability' tests, rely on application of a tracer material that can be readily applied evenly across a test surface and its presence determined *in situ*. An example is the use of rhodamine, which fluoresces under UV illumination (Lerch et al. 2013), where digital camera technology allows the distribution of tracer to be mapped where the surface can be viewed. The level of soil which can be detected varies between applications and imaging conditions. The aim of cleanability tests can be simply to confirm that the cleaning agent can access the surface to be cleaned, and can be very effective at this. For such a testing method to be useful for cleaning studies, it must be capable of quantifying the amount of soil present over a useful range. Assays based on fluorescence and other phenomena can be sensitive to small amounts of soiling material but this sensitivity can lead to saturation limits with larger amounts and thus be less well suited to some cleaning studies.

Many cleaning studies involving model soils are aimed to quantify the rate of removal in order to understand the mechanisms involved, for scale-up, and to transfer the results to other systems. This requires quantification of the amount of soil present. Table 3 summarises techniques employed to study model soils, with an emphasis on

techniques that can be applied *in situ* and in real time. Transferring a soil sample to make measurements *ex-situ* induces time delays and changes in environment which can increase systematic errors into the measurements or interpretation of the results. Similarly, tests which require soil samples or deposits to be removed from a test surface for measurement can disrupt structure and change properties, or are not well suited to the measurements required, such as determination of adhesion strength.

The techniques identified in Table 3 cover a range of modern analytical methods as well as bespoke systems developed specifically for measuring soiling layers or fouling deposits *in situ* (*e.g.* high temperature quartz crystal microbalances, micromanipulation, immersed millimanipulation, and fluid dynamic gauging). One of the factors limiting the adoption of high resolution chemical analysis methods is the heterogeneity and multi-phase nature of food soils, discussed by Cuckston et al. (2019): when the soil is a composite, with voids, droplets or inclusions with length scales of several microns, the composite response needs to be measured and related to any individual component response.

Table 3 separates methods to measure the amount (mass coverage) of a soil layer from volumetric methods, as the latter allow swelling and shrinkage effects to be quantified. In some cases, direct measurements of mass and volume are desired, as relating these can provide insight into the preferred removal of components in a composite soil (*e.g.* by leaching of soluble material). The label 'wet' indicates if the soil can be measured in its original state or if, for excample, drying or shrinking effects have to be considered.

The distribution of structural features, mechanical and thermal properties are often of interest, particularly in the validation of detailed cleaning models. The labels 'local' and 'overall' indicate whether the technique offers measurements at individual locations or averaged over a measurement region, while 'scan' indicates that the technique can make many local measurements over an area. The challenge with local measurements is whether they offer a reliable description of the ensemble behaviour, while overall measurements can often be explained by more than one distribution. Scanning methods are ideal, but these can take more time than is available.

Each of the techniques in Table 3 is subject to mechanistic limitations which will determine its suitability for studying a given combination of model soil and cleaning conditions. There will also be limitations associated with physical access, speed of cleaning (both short and long timescale processes bring challenges) and cost. The accuracy and reliability of the measurements also vary between applications.

5. High-protein model systems

5.1. *Milk related model systems*

The heat treatment of dairy fluids invariably results in fouling deposits, the cleaning of which is a major cost for the industry. The type of deposit formed depends on the processing conditions, but even today they are roughly classified following the work of Burton (1968) as type A, formed at 75–110 °C and consisting mostly of proteins, or type B, formed at > 110 °C and consisting mostly of minerals (principally calcium phosphate). Many more cleaning studies have been conducted on type A protein-rich deposits since the pioneering work by Jennings (1965) using radiolabelled proteins, arguably because they are simply easier to form and reproduce than type B deposits, from *e.g.* UHT. Type A deposits have been deconstructed with many different model materials in the past four decades, whereas progress on mineral rich deposits is more limited (see Hagsten et al. 2019a). Table 4 presents an overview of model soils used to represent Type A deposits.

By the early 1990's there was already a good phenomenological description of dairy cleaning. For example, Jeurnink and Brinkman (1994), using semi-industrial heat exchangers and evaporators processing milk and whey, provided major observations on the cleaning process, and presented the motivation to consider simpler deposit materials than real fouling layers: "*It is not known which chemical reaction causes the formation of the rubber-like layer since little research has been done on proteins under the conditions applied during cleaning*". Similar fundamental questions could have been raised by the authors on other cleaning observations, *e.g.* how protein deposits swell in alkali; how such deposits are mechanically degraded; how do hydroxyl ions move into deposits; or even more importantly, which are the chemical reactions that occur during alkaline cleaning of these soils.

As presented in Section 2.2, there are many levels at which dairy fouling deposits can be simplified. However, the main simplification involved using commercial whey protein powders instead of raw milk. It was long recognized that type A deposits were disproportionately composed of whey proteins, despite these only representing about 5% of the total solids in milk (Lalande and Tissier, 1985). Such composition was congruent with how such deposits were formed, mainly dependent on the thermal denaturation of whey proteins, and on β-lactoglobulin (βLg) in particular (Jong, 1997). βLg defines the characteristics of the deposits because it is the most abundant protein in whey, *e.g.* 50% *vs* 5% for bovine serum albumin (BSA), and it can readily aggregate and polymerize once denatured, unlike α-lactalbumin (20% of whey) which does not have a free cystine (thiol group) to form disulphide crosslinks. How these proteins, the main components of whey protein powders, thermally denature and subsequently aggregate is extensively documented in the literature (Havea et al. 2001).

Using reconstituted whey protein solutions, at similar concentrations to those found in milk, has allowed fouling deposits to be generated readily and reproducibly, resulting in repeatable cleaning experiments (Gillham et al. 1999). While such whey protein fouling deposits allowed the role of processing conditions during CIP to be investigated, such as the counter-intuitive role of the alkali concentration in the cleaning solution (Bird and Fryer, 1991), current understanding of the fouling procedures does not yet allow fouling deposits with tailored properties or characteristics to be generated, to investigate their effect on cleaning. On the other hand, the heat induced gelation of globular proteins is very well documented (Ziegler and Foegeding, 1990), and whey protein hydrogels with many different characteristics, such as microstructure, can be formed readily (Nicolai, 2019). Xin et al. (2002a) used highly concentrated protein solutions (*e.g.* 25 wt%) to form gels on pipe surfaces, instead of using low protein milk-like content solutions (*e.g.* 3.5 wt%). However, it is not surprising that different methodologies, with *ad hoc* fouling parameters such as heating temperature and protein concentration, result in deposits with different cleaning characteristics, as argued by Hooper et al. (2006b), if

Table 5 – Overview on meat-related model systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
BSA	Pure BSA (Sigma)	Superficial dried protein on 316 SS plate 30 × 50 mm	Drying at 37 °C for 90 min	Pipetting	Effect of electrical field and different enzymes	Protease solution (trypsin, a-chymotrypsin, and thermolysin)	FTIR (protein band)	Cleaning improves with an external electrical field	Htwe et al. (2017)
BSA	Pure BSA (Sigma)	Semi-infinite gel in plastic centrifuge tubes Ø 9 mm	15 wt% at 80 °C for 1 h	Gelation in a static tube	$T_{cleaning}$ 20–65 °C, added NaCl concentration 0.05–1 M, gelation pH 6–11	NaOH up to 7 wt%	UV spectroscopy	Presents some similarities to the dissolution of whey or βLg gels, but also significant differences - *e.g.* no optimum NaOH concentration	Mercadé-Prieto et al. (2018)
Gelatine	Pork gelatine (supermarket)	Dry gel layer on 316 SS disks Ø 50 mm	25 wt%, dissolved at 50 °C and then chilled	Pipetting	Dynamic swelling and removal with pH	NaOH pH 7–11.8 and commercial detergent	Scanning fluid dynamic gauging (sFDG)	Effect of swelling on removal	Gordon et al. (2010b)
Gelatine	As above	As above	As above	As above	Different detergents	Commercial biological dishwasher formulations	Scanning fluid dynamic gauging (sFDG)	Observed role of enzymes in removal	Gordon et al. (2012)

Table 6 – Overview of egg albumin model systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Egg albumin	Egg white powder	Adhered protein on 316 SS powder	2 g/L, 60 °C for 120 min	Incubation of steel powder with protein solution	Steel pretreatment with citric and nitric acid	NaOH	BCA method	Citric acid is efficient to reduce protein adsorption	Hagiwara et al. (2015)
Egg albumin	Ovalbumin powder (Sigma, A-5253)	Semi infinite gels in plastic centrifuge tubes Ø 9 mm	16.6 wt%, pH 6.4–10, 80–90 °C	Gelation in a static tube	Cleaning temperature 20–80 °C, NaOH concentration, gelation conditions	0.2–3 wt % NaOH	UV spectroscopy	Dissolution is first order with the alkali concentration; much higher activation energies and similar to β-elimination of disulfide bonds	Li et al. (2015)
Egg albumin	Crude egg white powder (81 wt% protein)	Thick gels	15 wt%,pH 7.2 and 11, 80 °C for 1 h.	Gelation and soluble aggregates	Swelling and stability of particulate aggregates	NaOH up to 2 wt%	Swelling and HPLC	The dissolution threshold is at a much higher pH than for whey proteins; stronger covalent crosslinking	Li et al. (2016)
Egg albumin	Ovalbumin powder (Sigma, A-5253)	Thick gels	7.5–13.8 wt%, 90 °C for 0.25–5 h	Gelation	Preliminary dissolution tests	0.3–5.7 wt%	UV spectroscopy	No optimum cleaning concentration; dissolution is faster with the alkali concentration	Li et al. (2013)
Egg albumin	Ovalbumin powder (Sigma, A-5253)	Fouling deposit on SS disks Ø 26 mm	3.75 wt%, 80 °C for 30–90 min	Static fouling over a disk coupon	Adhesion and cohesion tests, and traditional cleaning tests of coupons	0.1–3 wt % NaOH	Pulling force, images and heat transfer coefficient	Cohesive strength greater than adhesive strength; time to clear is continuously reduced with higher alkali concentration	Liu et al. (2007)

the deposits formed are quite different, particularly in protein content.

Being able to generate reproducible and relatively thick deposits, using whey protein solutions, allowed researchers to investigate the cleaning procedure in detail using different monitoring techniques, such as UV-Vis for cleaning rates (Xin et al. 2002a) and fluid dynamic gauging (FDG) for deposit thickness (Tuladhar et al. 2002a). It was observed that there is initially a clear swelling stage, whereby protein removal is limited, followed by a period where the cleaning rate is high and constant, often termed R_o, and finally a decay stage in the cleaning rate until the whole surface is clean. This three stage paradigm, where R_o could be observed over long periods due to the use of thick deposits (Xin et al. 2002a), replaced previous explanations using empirical mathematical models (Dürr and Graßhoff 1999). These observations raised fundamental questions on how cleaning happens, such as which mechanism(s) is responsible for R_o.

It was soon realized that such questions went beyond the problem of cleaning, and that their complexity was such that the number of experiments required to investigate them would be unfeasible to perform as fouling deposits. This led to the second major simplification in dairy cleaning: to focus on the protein deposits themselves, and to omit the role of the substrate – considered to be relevant in the final decay stage. This led to the subsequent use of whey protein hydrogels, created under well-defined conditions (*e.g.* protein concentration (Fickak et al. 2011), temperature (Mercadé-Prieto et al. 2006), salts (Mercadé-Prieto et al. 2007c), pH (Fan et al. 2019b), *etc.*), instead of deposits formed on a metal surface mimicking a heat exchanger. To clearly differentiate this new type of study, the term "dissolution" was often used rather than "cleaning", drawing on links to similar processes with *e.g.* polymers (Hunek and Cussler, 2002).

Meanwhile it is straightforward to create different variants of model deposits by heating whey proteins, in the presence or absence of a surface, only hydrogels formed at constant gelation conditions are currently well understood (Havea et al. 2009). Some model deposits reported in the literature are difficult to understand in terms of mechanisms due to the way they were formed. An example is the soiling procedure of Jurado-Alameda et al. (2014), in which a stainless steel scourer was dipped in a 45 wt% whey protein solution, left to drain excess liquid off then autoclaved at 121 °C for 1 h, followed by drying at 60 °C for 12 h. As such, this represents a 'standard' soil (Table 1).

The use of simple whey protein hydrogels, for example 15 wt% solutions heated at 80 °C for 30 min, has generated substantial insights on the fundamentals of cleaning. For example, the relevance of the gelation conditions demonstrated by such studies was essential to disprove the hypothesis the cleaning was dominated by the external mass transfer (Mercadé-Prieto and Chen, 2006). Subsequent studies highlighted, instead, the role of breakdown reactions between proteins, particularly hydrophobic interactions between proteins for whey protein hydrogels (Fan et al. 2019b). Such model hydrogels are essential to understand the swelling that occur in cleaning solutions, at equilibrium (Mercadé-Prieto et al. 2007a) and dynamically (Saikhwan et al. 2010), as well as the mechanical degradation (Hu et al. 2017) and composition (Xu et al. 2018) of the hydrogels as they swell and dissolve.

Nevertheless, it is essential to confirm that the model system selected presents sufficient similarity to the real

Table 7 – Overview of plant-based protein-rich model systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Rubisco	Extracted from spinach and subsequently purified	Adsorbed protein layer on cellulose surface	0.5 g/L recirculated for 1 h, room temperature	Immobilization on cellulose monolayers	Concentration of enzyme	Enzyme (subtilisin A)	Surface plasmon resonance	Enzymatic modelling	Onaizi (2018)
Rubisco	As above	As above	As above	Immobilization on hydrophobic and hydrophilic monolayers	Surface properties, crosslinking adhered proteins	As above	As above	Determination of proteolysis and enzyme deactivation rate constants; marked effect of substrate on cleaning performance	Onaizi et al. (2009)
Soy protein	Soy protein isolate 90 wt%	Semi-infinite gel in plastic centrifuge tubes Ø 9 mm	13 wt% with 0.1 M NaCl, 95 °C for 1 h	Gelation in a static tube	Cleaning temperature 25–80 °C, NaOH concentration, added salts (NaCl, CaCl2)	NaOH up to 6 wt%	UV spectroscopy	Some dissolution traits are similar egg white and others to whey proteins; influence of large protein sizes	Mercadé-Prieto et al. (2016)

Table 8 – Overview of starch-based model systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Native maize starch	Cerestar	Dry soil layer on glass plates $36 \times 26\ mm^2$	Dispersion of 6% starch in water at 100 °C for 30 min, then at 50 °C for 30 min	Coating of starch solution at 50 °C with scraper and drying at 60 °C for 2 h to 75 µm	Immersion in stirred beaker $T = 20–55$ °C, different surfactants, pH 9–11	2 alkaline, 7 complexing, 3 surface-active and 1 enzymatic agents	Optical inspection, partial addition of iodine / potassium iodine-solution	Temperature and fluid velocity improves detergency, as well as the addition of most of the complexing and of anionic and enzymatic agents. Adhesive failure, for the enzyme cohesive failure	Cerny et al. (2001)
Maize starch, wheat starch, rice starch, potato starch, modified potato starch	11.5–21% moisture	Dry soil layer on plates $13 \times 13\ cm^2$ of polished and rough glass, porcelain, SS with different roughness	Gelatinisation of an aqueous solution of 6% starch by heating at 100 °C for 30 min, cooling to 50 °C for 30 min	Coating of 2 mL starch solution with scraper (100–500 µm thick), drying at 60 °C for 2 h, storing in dessicator	Commercial dishwasher Different soils and surface materials	Commercial dishwashing agent	Removal of soil residues with NaOH in ultrasonic bath and photometric analysis with anthrone/ sulphuric acid method	Maize starch on glass plates is most suitable. Removal mechanism not specified	Linderer and Wildbrett (1993)
Potato starch, maize starch, rice starch, waxy maize starch	Native and derivatised varieties	Wet soil layer on glass plates $6 \times 13\ cm^2$	Gelation similar to above. Cold swelling starches dissolved in water at room temperature	Coating similar to above, layers 50 – 250 µm thick, resulting in coverage of 14 – 83 mg/ plate	No cleaning tests conducted		Anthrone method recommended		Lang et al. (1991)
Modified waxy maize starch, potato starch	90% carbohydrates 8% moisture Maisita, 90% carbohydrates 8% moisture Agandyn	Dry soil layer on SS plates $40 \times 20\ mm^2$	Aqueous suspension of 1% starch stirred at room temperature for 12 h	Coating of 100 µL starch suspension with pipette on $2\ cm^2$ plate and drying at 55 °C for 1 h, partially modified by changing pH (3 and 9), drying at 90 °C for 1 h or heating the suspension to 82 °C for 2 min	CIP in continuous flow cell system at 54 mL/min and 21 °C. Different structural properties by alkaline, drying and preheating treatment	0.007% Lugol's solution	UV/VIS and micro-balance	Effects of thermally induced structural changes are not significant. Lower energetic or lower cationic charged soils are easier to clean. Cohesive failure	Otto et al. (2016)
Modified waxy maize starch	Sigma	Aggregates on glass, SS, polystyrene and	Suspension of 20% starch granules in water, adding	Manual aspersion with thin layer chromatography	Cleaning in radial flow Flow rate 20–390 mL/min	Water	Epifluorescence, AFM, SEM, contact angle, X-ray	Adherence of starch aggregates is influenced by substrate surface energy	Detry et al. (2011)

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– Table 8 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
		PTFE plates 50 × 50 mm^2	0.02% sodium fluoresceinate	sprayer, drying in dark cupboard at room temperature for 30 min and 1 week or in a exicator at 5 °C for 1 week			photoelectron spectroscopy (XPS)		
Native maize starch	11.5% moisture Maizena (Unilever)	Wet soil layer on glass spheres Ø 3 + 6 mm and discs of polyurethane Ø 8 mm	Gelatinisation of an aqueous solution of 8% starch by heating at 75 °C for 1 h then cooled	Submersion of discs in starch gel, compressing, and draining. Mixing of spheres and starch gel in beaker	CIP in bath-substrate-flow system at 30 L/h (v = 16 mm/s), 60 °C for 15 min. Different surfactants, 1–2 g/L	Enzyme α-amylase, anionic and ionic surfactants	Total soluble carbohydrates in washing solution by phenol-sulphur colorimetric method	No significant temperature effect on detergency for glass spheres but for polyurethane discs. Same for different surfactants. Removal mechanism not specified	Jurado-Alameda et al. (2011a)
Native maize starch	As above	Wet soil layer on Ø 8 mm polyurethane discs	Similar to above, heating at 70 °C for 1 h and cooling down for 12 h	Submersion of discs in starch gel, compressing, draining on mesh for 0.5 h and drying at 60 °C for 12 h, resulting in a mass of 1.9 g/plate	CIP as above Various surfactants and mixtures, 1 g/L, with different contact angles	2 non-ionic and 1 zwitterionic surfactants	Total soluble carbohydrates as above. Kinetics by weighing over 5–30 min period	Highest detergency for lower contact angles. Hydration process is important. Cohesive failure	Jurado-Alameda et al. (2016)
Native maize starch	90% carbohydrates 8% moisture Maizena (Unilever)	Dry soil layer on spherical wads of SS fibres	Gelatinisation of an aqueous solution of 8% starch by heating at 70 °C for 1 h and cooling down for 12 h	Submersion of wads in starch gel and drying on grate in oven at 60 °C for 12 h	CIP as above. T = 40–60 °C, enzyme concentration 0–1 g/L, 1 g/L different surfactants	Enzyme α-amylase, 3 anionic and 4 non-ionic surfactants	Total soluble carbohydrates as above	Temperature improves detergency. Surfactants effect negligible. Washing in absence of enzyme demanded high pH and temperature for a long time period. Removal mechanism not specified	Jurado-Alameda et al. (2015)
Native maize starch	As above	As above	As above	As above	CIP in bath-substrate-flow system at 40 °C for 45 min. Flow 30–60 L/h (v = 16–32 mm/s), 2 surfactants, silica	2 non-ionic surfactants	Total soluble carbohydrates as aboe	Maximum detergency at the highest level of pH, particle concentration and flow rate. Removal mechanism not specified	Herrera-Márquez et al. (2019)

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– Table 8 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
					microparticles 0.5 and 1 g/L				
Native maize starch	As above	As above	As above	As above	Electrocleaning device. Voltage 0–10 V, polarity. Inversion, temperature 10–60 °C, pH 1–10, wetting time 10–20 min, cleaning time 10–20 min	HCl, Sörensen's phosphate buffer, sodium carbonate-bicarbonate buffer, NaOH	Weighing	Detergency significantly higher with increasing voltage, temperature and time. Effect of polarity inversion, wetting time pH negligible. Cohesion failure, adhesion failure attributed to bubble formation on electrodes	Vicaria et al. (2018b)
Native maize starch	As above	As above	As above	As above	Electrocleaning device at 5 V, pH 13 for 20 min Temperature 20 + 60 °C, different surfactants 1 g/L	3 anionic and 4 non-ionic surfactants	Weighing	Surfactants effect significant, regardless if anionic or non-ionic. Temperature improves detergency. Cohesion failure, adhesion failure by bubble formation on electrodes assumed	Vicaria et al. (2018a)
Native maize starch	11.5% moisture Maizena (Unilever)	As above	As above	As above	CIP in bath-substrate-flow system for 30–60 min, T = 40–60 °C. pH 3–13, Flow 30–60 L/h (v = 16–32 mm/s), 5 surfactants, silica microparticles 0–1 g/L	Ionic and 3 nonionic surfactants, enzyme, ozonation	Total soluble carbohydrates in washing solution by phenol-sulphur colorimetric method and weighing	Maximum detergency in the absence of enzymes with fatty alcohol and ozone, highest detergency with highest enzyme concentration and temperature Removal mechanism not specified	Vicaria et al. (2017)
Native maize starch	K-classic from local supermarket	Dry soil layer on SS plates 200 × 100 mm^2	Cooking of an aqueous solution of 5% starch for 30 s and cooling down to room temperature	Coating by applicator frame with 203 µm gap then drying in climate chamber at 40 °C and 50% RH	Spray cleaning 3 different spray heads, 3 surface finishes	Water	Cleaned area by optical inspection with digital camera, staining with Lugol's solution	No significant influence of the substrate finish	Gerhards and Schmid (2013)

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– Table 8 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Modified waxy maize starch	Not specified	Dry soil layer on SS half-circular test sections with continuous and abrupt expansions	Not specified	Coating of starch/ZnS suspension with scraper in stripes 1.5×210 mm^2 with thickness 60 µm, and drying to 40–50 µm	Pulsed flow CIP in closed-loop test rig, CFD simulation	0.5 wt% NaOH	Optical detection of local phosphores-cence	Pulsed flow improves local detergency. Removal mechanism not specified	Augustin et al. (2010)
Modified waxy maize starch	Not specified	As above	Pregelatinized and acetylated	Coating of starch/ZnS suspension with scraper in two stripes	Pulsed flow CIP in closed-loop test rig, CFD simulation. v = 1–2.2 m/s, waviness 0.2–1.5	0.5 wt% NaOH	Local phosphorescence detection method (LPD)	Pulsed flow improves local detergency. Removal mechanism not specified	Föste et al. (2013)
Modified waxy maize starch	Not specified	As above	Dispersion of 6% starch and 9% ZnS in water	Coating of starch/ZnS suspension with scraper in lamellar gaps of a mask, dried at room temperature to a thickness of 50 µm	CIP in closed-loop test rig at room temperature, v = 1–2.2 m/s. CFD simulation.	0.5 wt% NaOH	Local phosphorescence detection method (LPD)	Cleaning process is diffusion-controlled	Schöler et al. (2012)
Modified waxy maize starch	C*Tex-Instant (Cargill)	As above	Dispersion of 6% starch/ 2–9% ZnS in water	Paste coated by scraping over mask in a 5×20 mm^2 and 13×210 mm^2 stripe, dried at room temperature to a thickness of 5–10 µm	CIP in closed-loop test rig at 1 m/s and stationary in a reservoir at 23 °C. Varied soil roughness	0.5 wt% NaOH	Local phosphorescence detection method (LPD) and fluid dynamic gauging (FDG)	Rougher layers are easier to clean. Three stage cleaning process (swelling, removal, decay)	Gordon et al. (2014)

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– Table 8 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Modified waxy maize starch	C*Gel-Instant (Cargill)	Dry soil layer on SS plates $80 \times 150\ mm^2$	Dispersion of 15% starch/ 0.4% ZnS in water at 23 °C for 30 min	Spraying and drying in climate chamber at 23 °C and 50% relative humidity for 20 h	CIP in closed-loop test rig at 19.5 °C, v = 1–3 m/s, initial soil mass 40–60 g/m^2 CFD simulation.	Water	Coverage by phosphores-cence, weighing	Diffusive and cohesive failure. Velocity improves detergency. No influence of initial soil coverage on cleaning rate	Joppa et al. (2017a)
Modified waxy maize starch	C*Gel-Instant (Cargill)	As above, but pre-wetted	As above	As above	CIP in closed-loop test rig, 25 °C, v = 0.5–2 m/s, pre-wetting time 120 or 240 s, initial soil mass 30–50 g/m^2. CFD simulation.	Water	As above	Diffusive and cohesive failure. Velocity improves detergency. Pre-wetting enhances cleaning rate	Joppa et al. (2017b)
Modified waxy maize starch	C*Gel-Instant (Cargill)	As Joppa et al. (2017a)	As above	As above	As above, T = 25 °C, v = 0.5–2 m/s, initial soil mass 35–65 g/m^2. Validation with water jet	Water	Above	Diffusive and cohesive failure. Velocity improves detergency	Joppa et al. (2019)
Modified waxy maize starch	C*Gel-Instant (Cargill)	Dry soil layer on SS steel plates $500 \times 500\ mm^2$	Dispersion of 15% starch/ Lumilux (Honeywell) in water	Spraying and drying in climate chamber at indoor climate for 24 h resulting in mass coverage of 40 g/m^2	Water jet with full jet nozzle at 21 °C. Discontinuous flow	Water	Coverage by fluorescence, weighing	Discontinuous flow improves detergency, intermittent more than pulsed flow. Removal mechanism not specified	Fuchs et al. (2017)
Modified waxy maize starch	C*Tex-Instant (Cargill)	Dry soil layer on SS plates $20 \times 80\ mm^2$	Dispersion of 1.5 wt% starch powder in water at 35 °C for 30 min	Coating by scaper, 1 mm thick layer, drying in climate cabinet at 23 °C and 50% RH for 24 h	CIP in closed-loop test rig (Automated Particle Analyser for Cleaning - APAC). T = 20–50 °C, v = 0.25–0.75 m/s	Water, 0.25 wt % NaOH	Volume- and quantity-weighted particle size distribution	Temperature improves detergency with no influence on particle size distribution. Higher velocities and lye have a significant effect on particle size distribution. Cohesive failure	Sauk et al. (2018)

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– Table 8 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Modified waxy maize starch	As above	As above	Dispersion of 6 wt% starch powder in water at 35 °C for 40 min	As above, drying for 24 h to 115 µm	As above, Flow = 84 L/h (v = 10 mm/s). T = 23–60 °C	Water	Particle size distribution with laser diffraction method	Particle size decreases with temperature. Cohesive failure	Gottschalk et al. (2019)
Starch	Not specified	Film on SS coupons 1 cm^2	Suspension of 1 wt% starch in water	Casting of a drop of 0.05 mL	Mechanical cleaning with crock metre and high pressure spray cleaning Different surface finishes	0.1% dobanol 91–8 (Unilever)	X-ray photoelectron spectroscopy (XPS)	High pressure removed absorbed material much more effectively than mechanical action	Boyd et al. (2001)
Wheat starch	0.7 wt% ash Grüssing	Dry soil layer on SS half-circular test sections with abrupt expansion	Dispersion of 6 wt% starch in water autoclaved at 121 °C for 20 min, adding 9 wt% ZnS after 8 h	Coating of starch/Zn suspension with scraper in lamellar gaps of a mask, stored at room temperature for 24 h and dried at 60 °C for 2 h to a thickness of 20–30 µm	CIP in open-loop test rig, CFD simulation. T = 25 °C, v = 1 m/s	1 wt% NaOH	LPD, weighing	Method development, proof of concept	Schöler et al. (2009)
Potato starch	Neutral, anionic and cationic Cargill	Solid soil layer on SS plates 20 × 40 mm^2, partially coated with SiO_2 or silane.	Gelatinisation of a solution of 7 wt % starch in 10^{-3} M KCl by heating from 50 °C to 90 °C over 30 min, held for 30 min, stored at 60 °C	Coating by scraper to 10–250 µm and drying at 23 °C and 50% RH for 24 h, resulting in mass coverage of 0.2–1.6 mg/cm^2	Water jet with 90 ° flat fan nozzle at 1.77 L/min, 4 bar and 23 °C. Surface roughness, surface energy and electrokinetic properties	0.5 wt% NaOH	Fluorescence by adding 0.012% Uranin AP	Surface roughness effect negligible. Low-energy surfaces and surfaces with accordant surface charge are easier to clean. Cohesive failure	Mauermann et al. (2012)

Table 9 – Overview of other plant-based and microbial model soil systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Xanthan	Jungbunzlauer Xanthan GmbH	Wet soil layer on SS tubes	Dispersion of 2 wt% Xanthan in hot water with 3 wt% NaCl	Recirculation of dispersion for 5–10 min	Flushing behaviour in horizontal and vertical pipe systems, $T = 5–40$ °C and $v = 0.3–3.5$ m/s	Water, polyethylene glycol	Optical inspection, weighing, residual concentration by viscosity or conductivity measurement	Characteristic curves for the ratio of soil viscosity and shear stress	Welchner (1993)
Xanthan	Kremer Pigmente	Dry soil layer on SS plates $500 \times 500\ mm^2$	Dispersion of 0.5 wt% Xanthan/ Lumilux (Honeywell) in water	Spraying and drying in climate chamber at indoor climate for 24 h resulting in a mass of $11\ g/m^2$	Moving water jet with solid stream nozzle at 21 °C. 4 nozzle diameters	Water	Coverage by fluorescence, weighing	Higher jet traversing speeds give increased productivity in terms of rate of cleaning, energy requirement and liquid consumption per unit mass of soil removal. Removal mechanism not specified	Wilson et al. (2015)
Xanthan	Kremer Pigmente	As above	Dispersion of 0.8 wt% Xanthan/ Lumilux in water	As above, reported coverage $10\ g/m^2$	Water jet with full jet nozzle at 21 °C. Discontinuous flow	Water	As above	Discontinuous flow improves detergency, intermittent more than pulsed flow. Removal mechanism not specified	Fuchs et al. (2017)
Agarose	Sigma	Wet soil layers on SS, PTFE, enamel plates $20 \times 10\ mm^2$	Dispersion of 0.85% agarose/ fluorescein (Sigma) in water	Dispersed in water, surfactant added, boiled and cooled to 60 °C, spin-coating to give 20 µm thick layer	CIP in flow cell different surface roughness and structure	Water	Fluorescence microscopy	Cohesive failure	Bobe (2008)

system it aims to explain. Such analysis could consider that dissolution rates of hydrogels are comparable to cleaning rates of whey protein deposits (Mercadé-Prieto and Chen, 2006; Tuladhar et al. 2002a), that dissolution and cleaning rates increase pseudo-linearly with the alkali concentration up to ~0.1 M alkali (Jennings, 1965), or that at higher alkali concentrations both dissolution and cleaning rates markedly decrease (Bird and Fryer, 1991; Fan et al. 2019a). A parameter often used in dairy cleaning studies is the apparent activation energy, E_a, quantifying the temperature dependency of the cleaning rate. In as much as E_a values are related to the underlying rate limiting mechanism(s), the consistent agreement between dissolution experiments using model hydrogels and cleaning experiments using deposits, at 40–50 kJ/mol at < 0.1 M alkali and > 70 kJ/mol at higher concentrations (Fan et al. 2019b; Mercadé-Prieto et al. 2008; Tuladhar et al. 2002a), suggest that the conclusions obtained from the models are applicable to real deposits.

Finally, the ultimate simplification of the cleaning problem is not to consider a deposit layer, but the soluble protein aggregates that they are constituted from. Aggregates can be formed at the same temperatures and times than hydrogels, but at much lower protein concentrations, as in cold gelation studies (Marangoni et al. 2000). Such model systems are useful to study the alkaline breakdown reactions (Mercadé-Prieto et al. 2007b), or the role of aggregate microstructure in swelling (Li et al. 2016).

5.2. *Meat related model systems*

Table 5 shows that two materials have been commonly used to study meat soils. Bovine serum albumin, BSA, is a protein that can be readily found commercially, and it is also well known to form hydrogels (Boye et al. 1996) and can thus be used as model material in cleaning studies, *e.g.* the enzymatic cleaning of BSA absorbed on stainless steel (Htwe et al. 2017). Like βLg, BSA has many internal disulphide bridges (cysteines), but only one free cysteine to start covalent polymerization reactions. Mercadé-Prieto et al. (2018) found many similarities between the alkaline dissolution of BSA and βLg or whey protein gels, such as the importance of the different breakdown reactions with alkali. However, different behaviours were observed, such as a stagnation, and not a decline, of the dissolution rate at NaOH concentrations > 0.1 M. A key difference of BSA is its large size, at 66.5 kDa it is 3.6 times bigger than βLg, which could affect its release.

Gelatine is a blend of proteins derived from animal collagen, with a wide range of applications. Gels formed with gelatine are defined as physical gels because the inter-protein crosslinks are not permanent: they can be destroyed and reformed with temperature, whereas whey protein and BSA systems are described as chemical gels. In the latter, most of the crosslinks, and thus the gels themselves, are irreversible – hence chemicals are needed for cleaning (Ziegler and Foegeding, 1990). Gelatine has been used extensively as a model material to characterize swelling dynamics (Gordon et al. 2010b; Tsai et al. 2019; Wang and Wilson, 2015). However, extensive swelling does not imply dissolution nor removal. The removal of gelatine is clearly affected by the existence of a melting temperature, typically around 15–30 °C, but it depends on other parameters such as the molecular weight (Eldridge and Ferry, 1954) and the gelation conditions (Godard et al. 1978). For this reason, Föste et al. (2014) observed a small temperature increase, between 20

Table 10 – Examples of sugars as model soil systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Glucose syrup	Cerestar Deutschland GmbH	Viscous soil film on SS tubes 13–1000 Pa s at 50–10 °C	Solution, dry mass 82%	Recirculation of dispersion for 5–10 min	Flushing behaviour in horizontal and vertical pipe systems. pipe diameter, T = 5–40 °C, v = 0.3–3.5 m/s	Water, polyethylene glycol	Optical inspection, weighing, residual concentration by viscosity or conductivity measurement	Characteristic curves for the ratio of soil viscosity and shear stress	Welchner (1993)
Honey	Sainsbury's Basic	Viscous liquid film on SS discs Ø 50 mm 14 Pa s at 20 °C	Direct unchanged application	Pipetting at room temperature to a thickness of 3.5 mm	Scraping with blade in a millimanipulation device v = 1–4 mm/s	None	Scrape force measurement	Effect of layer rheology on deformation behaviour	Ali et al. (2015b)

Table 11 – Overview of plant cell and fibre as model soil systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Tomato paste	4.5% protein, 14.9% carbohydrates, 12.6% sugar 0.2% fat, 2.8% fibres (local supermarket)	Fouling deposits on SS discs Ø 26 mm	Direct unchanged application	Spreading on discs and heating in oven at 100 °C up to 240 min. Dried samples hydrated in water at 20 °C up to 75 min before testing	Removal behaviour Baking time 0–240 min, hydration time 10–75 min, deposit thickness 0.6–1.7 mm, 2 surface finishes	Water	Micromanipulation probe	Strength increased with baking time and thickness of sample, and decreased with increasing hydration time and temperature	Liu et al. (2002)
Tomato paste	Not specified	Fouling deposits on SS discs Ø 26 mm, uncoated and coated with Ni-P-PTFE composite	Direct unchanged application	As above, oven heating at 100 °C for 60 min. Dried samples hydrated in water at 20 °C up to 25 min before testing	Removal behaviour Baking time 0 and 60 min, hydration time 10–25 min, deposit thickness 1.2–3.6 mm, 2 surface materials	Water	Micromanipulation probe	Primarily adhesive failure observed. Effect of surface decreases with increasing deposit thickness	Liu et al. (2006a)
Tomato paste	Not specified	Fouling deposits on SS and leaded phosphorus bronze discs Ø 20 mm	Direct unchanged application	As above	Similar to above, deposit thickness 3.2 and 1.7 mm, cutting height 20–1500 µm	As above	As above	At small cutting heights the work needed to remove the deposit increases with height and is a function of the nature of the surface, whilst at larger heights the work needed decreases and is not a function of the surface	Liu et al. (2006b)

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– Table 11 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Tomato paste	4.7% protein, 14.9% carbohydrates, 14.4% sugar 0.4% fat, 2% fibres (local supermarket)	Fouling deposit on Ø 30 mm SS discs	Direct unchanged application	Spreading to 2 mm on discs and heating/ drying in a vacuum oven at 100 °C for 0.5–4 h. Dried samples hydrated in RO water at 18 °C for more than 1 h before testing	Shear strength and micro-structure Drying time 0.5–4 h	Water	FDG and SEM	Shear strength increases with the extend of ageing.	Chew et al. (2004)
Tomato paste	4.7% protein, 14.9% carbohydrates, 14.4% sugar 0.4% fat, 2% fibres (local supermarket)	Fouling deposit on Ø 20 mm discs: SS and SS with DLC and sol-gel coatings	Direct application	Spread 2 mm thick on discs, oven heated at100 °C for 90 min. Dried samples hydrated as above at 20–22 °C for 45 min before testing	Adhesive interaction Various surface modifications	Water	FDG	Adhesive and mixed failure could be observed, indicating that the adhesive interactions vary with surface interactions	Saikhwan et al. (2006)
Tomato paste	4.7% protein, 14.9% carbohydrates, 14.4% sugar 0.4% fat, 2% fibres (local supermarket)	Fouling deposit on SS plates 25 × 160 mm^2	Direct application	Spreading to 1 mm on plates, dried at 20 °C for 24 h and baked in oven at 100 °C for 30–180 min to a thickness of 500 µm	Swelling kinetics and deformation behaviour at 20 °C Different baking times	RO water	Scanning fluid dynamic gauging (sFDG)	Similar swelling rates, but earlier rupture for shorter baking times	Gordon et al. (2010a)
Tomato paste	Sainsbury's double concentration	Fouling deposit on stainless steel discs Ø 26 mm	Direct application	Spread on discs and heating in oven up to 180 min. Dried samples hydrated in water at 20 °C up to 105 min before testing	Removal behaviour Baking time 0–180 min, hydration time 10–105 min, 2 surface finish	Water	FDG and micromanipulation	Both techniques show marked and quantifiable effects of baking and hydration time on removal behaviour	Hooper et al. (2006a)

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Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Hop tanning agent	Concentrate (Hallertauer Hopfenveredlungsgesellschaft)	Wet soil layer on stainless steel tubes	Aqueous mixture of 83–99.8% hop tanning agent concentrate and 0.2–0.5% Xanthan gum	Recirculation of dispersion for 5–10 min	Flushing behaviour in horizontal and vertical pipe systems pipe diameter, T = 5–40 °C and v = 0.3–3.5 m/s	Water, polyethylene glycol, air	Weighing, residual concentration by density measurement	Characteristic curves for the ratio of soil viscosity and shear stress	Welchner (1993)
Pink guava purée	Pink guava purée 0.8% protein, 0.2 fat, 3.4% carbohydrate	Hard, sticky and tenacious layer 1 mm thick on 15 × 45 mm² stainless steel plates	2 g pink guava puree	Purée evenly spread on substrate, heated in oven at 100 °C for 1 h	Development of a test rig for cleaning experiments including detection method for these deposits T = 35–70 °C, v = 0.6–1.5 m/s	Water with 0–2 wt% NaOH	Optical detection with video camera	Temperature and NaOH concentration are most important for cleaning effect	Khalid et al. (2015)
Pink guava puree	As above	As above	As above	As above	Cleaning kinetics T = 35–70 °C, v = 0.6–1.5 m/s	Water with 0–2 wt% NaOH	Optical detection with video camera	4-step CIP cycle with only 2 min long alkaline cycle (1.5 wt% NaOH) at 70 °C (step 2) is most appropriate	Khalid et al. (2016)

Table 12 – Overview of fats as model soil systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Lard	Lard from local market	Soft solid layer on Ø 3 mm glass spheres	Direct application	Mixing of glass spheres and lard and storing for 30 min at 4 °C	CIP in bath-substrate-flow system at 30 L/h (v = 16 mm/s) and 60 °C for 10 min. Various surfactants and mixtures 1 g/L with different contact angles	2 nonionic, 1 zwitterionic surfactants and ozone	Weighing	Highest detergency for lower contact angles	Jurado-Alameda et al. (2016)
Lard	Lard from local market	As above	As above	Soiling of glass spheres with 0.1 g/g lard	Similar to above, 65 °C for 10 min. Different surfactants with ozonation	2 nonionic, 1 anionic surfactants and 1 enzyme	Spectrophotometry	Detergency effect of ozone alone is small, but can deactivate surfactants	Jurado-Alameda et al. (2012)
Lard	Sainsbury's Basic	Applied as soft solid layer on Ø 50 mm SS discs: structure depended on heating	Direct application	Coating with spatula in a ring with a thickness of 0.9 mm or pipetting to 200 µm and baking for 1–5 h at 50–250 °C. Partial addition of ovalbumin (0–9.5 wt%)	Scraping with blade in a millimanipulation device Scrape speed 1–4 mm/s		Scrape force measurement	Cohesive failure for unbaked and adhesive failure for baked lard Addition of ovalbumin delayed the onset of polymerisation	Ali et al. (2015b)
Butter	Tesco butter spread	Soft solid layer on stainless steel plates 150 × 15 mm^2	Direct unchanged application	Coating with knife-edge in a jig with a thickness of 1 mm	Thickness of soil layer, dependency of clearance from mass flow in nozzle and calibration	Water	FDG	Method development, proof of concept	Tuladhar et al. (2000)
Sunflower oil	13% fatty acids 22% monounsaturated acids (oleic acid) 65% polyunsaturated acids (Lesieur, France)	Liquid film on stainless steel plates	Direct unchanged application	Spraying, resulting in a droplet layer Ø < 1 µm with a soil density of 0.7 mg/cm^2, or film application with a thickness of 120 µm and a soil density of 7–8 mg/cm^2	CIP in laminar flow cell Various surface finishes and coatings	Commercial cleaning agent	Weighing	The larger the polar component of the surface energy, the better the cleaning performance, except for engraved surfaces	Boulangé-Petermann et al. (2006)

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– Table 12 (*Continued*)

Soiling					Cleaning				Reference
Material	**Composition Product, Supplier**	**Structure & classification**	**Production conditions**	**Soil application**	**Investigation & varied parameters**	**Agent**	**Detection method**	**Effect & classification**	
Sunflower oil	13% fatty acids 87% unsaturated acids (Carrefour, Belgium)	Droplets on SS, glass, polystyrene and PTFE plates $50 \times 50\ mm^2$	Direct application	Thin layer chromatography spraying, resulting in droplet Ø 10–100 µm, or scrubbing with brush, resulting in droplet Ø 10–200 µm	Radial flow cell at 20 °C Different surface materials, flow = 190 and 390 mL/min, time = 0.5–15 min	Commercial cleaning agent	Diameter of circular area free of oil, using calipes or stereomicroscope	Glass was most cleanable: for the other substrates the fluid mechanic plays the major role in oil removal	Detry et al. (2007)
Mayonnaise	80% soybean oil 10% water 5% emulsifier 4% acetic acid (10%) 1% NaCl	Soft solid layer on SS tubes	Direct application	Recirculation of dispersion for 5–10 min	Flushing behaviour in horizontal and vertical pipe systems. Pipe diameter, T = 5–40 °C and v = 0.3–3.5 m/s	Water, polyethylene glycol	Optical inspection, weighing, fat content in washing bath	Characteristic curves for the ratio of soil viscosity and shear stress	Welchner (1993)
Fatty acids	Oleic, palmitic and stearic acid	Soft solid coating on Ø 3 mm glass spheres	Mixture of fatty acids, 74% oleic acid	Dousing of the glass spheres	CIP in bath-substrate-flow system at 30 L/h (v = 16 mm/s) for 10 min Different surfactants, concentration 0.05–3 g/L, soil concentration 10–22 g/L, T = 40–55 °C	2 nonionic surfactants	Acidity index of the washing bath at different times	Surfactant has an effect until the melting point is reached	Jurado-Alameda et al. (2011b)
Lipid nano particles	10% carnauba wax	Particulate deposit in SS micro channels 100, 200 and 400 µm	High pressure homogenisation	Direct soiling in apparatus in preceding process	Cleaning of micro structured heat exchanger for 25 min Flow rates 5–25 mL/min	Ethanol, acetone	Automated local optical inspection by digital microscope	Method development, proof of concept. Detection of decreasing and increasing local soil coverage during cleaning	Schoenitz et al. (2014)
Lipid nano particles	5% carnauba wax, 10% decyl oleate, 2% emulsifier	Particulate deposity on SS plates $80 \times 20\ mm^2$	As above	Spraying with nebulizer on substrates preheated to 45 °C and dried for 24 h	Cleaning of micro structured heat exchanger T = 20–95 °C	Water, commercial alkaline cleaning agent	Fluid dynamic gauging (FDG) and weighing	Macroscopic methods cannot be transferred directly to micro devices but qualitative statements for an optimized cleaning concept are possible	Schoenitz et al. (2015)

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– Table 12 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Coconut milk	Fresh coconut meat 2.6% proteins, 32% fat	Soft solid layer on SS plates $10 \times 70\ mm^2$ or $25 \times 120\ mm^2$	500 g coconut meat shredded in 200 mL water at 45 °C	(1) Batch process in a vessel heated to 70 °C, held at 20 min, $T_{surface}$ = 80–90 °C; (2) Continuous flow channel heated from 65 °C to 70 °C, $T_{surface}$ = 92 °C	Swelling and dissolution pH 7–12	NaOH	Layer thickness and strength with FDG, weighing	Thickness and strength increased with pH for both types of deposits. Adhesive strength of deposit from continuous process is considerably larger than that of the batch process	Saikhwan et al. (2015)
Coconut milk	Fresh coconut meat	Soft solid layer	500 g coconut meat shredded in 200 mL water at 45 °C	Continuous process in a flow channel heated to 70 °C	Swelling and dissolution of soil in beaker and shaking incubator	Cellulase and protease	Weighing	Cleaning with cellulase and protease consecutively is most effective	Chutrakul et al. (2018)

and 26 °C, between extensive swelling, and swelling followed by removal. Gordon et al. (2012) used gelatine layers to study the performance of enzymatic detergents.

5.3. *Egg albumin*

Heat treatment of egg white solutions, *e.g.* for pasteurization, presents similar fouling problems to milk (Ling and Lund, 1978). Table 6 summarizes model egg soils. Crude egg white powders are available commercially and have been used as model proteins in fouling and cleaning studies (Hagiwara et al. 2015). Ovalbumin, with size ~43 kDa, is the main protein in egg white, and its gelation characteristics have also been investigated (Broersen et al. 2006). Cleaning studies with model egg white gels have shown noticeable differences in behaviour to whey protein gels: they dissolve much more slowly (Li et al. 2015) and require a higher pH (Li et al. 2016). In addition, egg white gels do not present an optimum alkali concentration: dissolution has been reported to increase with higher caustic concentrations (Li et al. 2013). Similar heat-set egg white gels were used as model deposits for cohesive and adhesive tests (Liu et al. 2006b), and showed substantial differences to milk protein deposits.

5.4. *Plant-based protein-rich systems*

There has been relatively little work to date on cleaning of plant-based soils, see Table 7. Rubisco is a major protein of green plants and has been used as a model for grassy stains, particularly in the enzymatic cleaning studies of fabrics (Onaizi, 2018; Onaizi et al. 2009). Rubisco is often extracted from spinach leaves and purified using chromatography. Soiling of the surfaces of interest is done by simple adsorption, although the immobilized proteins can be crosslinked with glutaraldehyde to elucidate better enzymatic cleaning.

A new food fouling problem has been reported in the evaporation of thin stillage, the stream containing dissolved solids generated by the fermentation of corn to produce bioethanol, of major economic relevance in the USA (Challa et al. 2017). Preliminary research has shown that the deposits formed contain around ~20 wt% (d.b.) protein (Wilkins et al. 2006), similar to those in dairy fouling. Recently, You et al. (2020) used glucose-yeast suspensions as model fouling fluids for this application, but cleaning of such deposits has yet to be investigated.

Commercial soy protein powder is composed of a varied mixture of proteins, mainly glycinin (11S globulins) and conglycinin (7S globulins), with complex quaternary structures and a wide size range (*e.g.* 17–170 kDa). Soy protein mixtures are substantially more complex than the other model protein systems discussed here. They often contain an insoluble fraction, hence it is not surprising that the understanding on how such hydrogels dissolve is still limited. Their dissolution behaviour lies between that observed for whey proteins and egg white, yielding similar dissolution rates to whey proteins, but with rates that increase linearly with alkali concentration up to 1 M NaOH (Mercadé-Prieto et al. 2016).

Table 13 – Overview of egg yolk soils.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Egg yolk	Emultherm Ovobest 31% proteins 57% fats	Dried soil layer on SS plates 115 × 28 mm² (inlet) and 145 × 43 mm² (outlet)	Dispersion of 800 g/L in water for 45 min	Coating with scraper, baking at 80 °C for 9 min, drying at 23 °C for 24 h and 50% rel. humidity	Cleaning model before and after sudden expansion 27–60 °C, 9.6 L/min - 86 L/min, substrate	0–1.82 wt % NaOH	Local phosphorescence detection method (LPD)	Cohesive removal in outlet region, adhesive removal in inlet region	Helbig et al. (2015)
Egg yolk	As above	As above, 115 × 28 mm²	As above	As above	Cleaning model for different soils	0–2% NaOH	LPD	Longest cleaning time was observed at approx. 1.2 wt% NaOH concentration	Deponte et al. (2018)
Egg yolk	As above	As above, 80 × 20 mm²	As above	As above	Particle size distribution of detached soil particles 23–60 °C	0–2% NaOH	Particle size measuring instrument	Detached egg yolk particles have a size of approx. 1 µm, particle size is not influenced by cleaning parameters	Gottschalk et al. (2019)
Egg yolk	As above	As above	Dispersion of 600 g/L in water for 45 min	As above	Normal and shear stress to remove soil by impinging jets fluid velocity, swelling state, jet angle	Water	Optical detection with camera under UV light, weighing of soil mass	Ellipses in stress diagrams for a certain swelling state can be predicted from only two normal and shear stress measurements	Murcek et al. (2019)
Egg yolk	As above	As above 115 × 28 mm² (inlet) and 145 × 43 mm² (outlet)	Dispersion of 1 g/g in water for 45 min	As above	Swelling, rheologcial and micromanipulation measurements 24–60 °C	0–1.82 wt % NaOH	LPD	Micromanipulation experiments are most suitable for cleaning time prediction	Helbig et al. (2019)
Egg yolk	DM-21, Center for Testmaterials B.V.	Approx. 70 µm thick (unbaked) dried soil layers on melamine tiles	Not specified	Spray coating, baking at 150 °C for 0 h, 1 h or 2 h	Influence of enzymes on swelling of egg yolk soil	Commercial cleaning agents with and without enzymes	Scanning FDG	Baked egg yolk is more challenging to clean and enzymes enhance shear stress removal	Gordon et al. (2012)
Egg yolk	Center for Testmaterials B.V.	Approx. 68 µm thick layers on SS tiles 120 × 100 mm²	Not specified	Spray coating	Swelling & removal of soil 30–50 °C	pH 10.5 with and without protease	Scanning FDG	Swelling of soil is necessary for following constant removal rate	Pérez-Mohedano et al. (2015)
Egg yolk	Center for Testmaterials B.V.	As above	Not specified	Spray coating	FDG, Diffusion of cleaning agent into the soil layer 30 + 55 °C	Na_2CO_3 or NaOH, pH 9.5–11.5	Scanning FDG and weighing	Swelling of soil is strongly influenced by temperature and pH, swelling curves can be described by Fickian diffusion	Pérez-Mohedano et al. (2016)
Egg yolk	Center for Testmaterials B.V.	As above	Not specified	Spray coating	Cleaning model for automatic dishwasher developed from FDG data 30 + 50 °C	Na_2CO_3 or NaOH, pH 9.5–11.5, with 0.02–0.1 g/L enzymes	Scanning FDG and automatic dishwasher	First draft of cleaning model for automatic dishwasher could be developed from FDG experiments	Pérez-Mohedano et al. (2017)

6. High-carbohydrate model systems

6.1. Starch-based model systems

Starch is a polysaccharide consisting of glucose units, formed in plants as a reserve carbohydrate, and is an important part of the human diet. In addition to carbohydrates, starch also contains very small amounts of proteins, lipids and minerals. (Ternes, 2008; Witt, 2010). Starch grains can swell in water and can also form pastes or gels of high viscosity at higher temperatures. During gelatinisation, the grain structure of the starch is destroyed, which leads to a sharp increase in viscosity. A further increase in temperature results in a decrease in viscosity. Cooling of the starch solution leads to a renewed gelatinisation and thus to an increase in viscosity. This process is called retrogradation (Ternes, 2008). It should be noted that the water affinity and thereby the structural properties of the starch layer are very sensitive to the (pre-) treatment, which is important for model soil studies, see Table 8.

Starch is present in many plants in large quantities and is harvested from potatoes, corn, wheat, peas, rice, barley, rye and the roots of manioc plants. The gelatinisation temperature and the swelling power depend on the plant used for starch production. Starch modification is performed to achieve certain functional properties, both on the native starch grain and after gelatinisation. Examples of starch modification are acidic hydrolysis, esterification, cross-linking, oxidation and etherification (Ternes, 2008).

Many publications on the cleaning of starchy soils can be found in the literature as starch is both in widespread use and starch soils are one of the more difficult food deposits to remove. For example, Linderer and Wildbrett (1993) as well as Cerny et al. (2001) both studied the cleaning of different types of starch in dishwashers, focussing on soiled glass surfaces. Linderer and Wildbrett (1993) proposed a native maize starch as a standard model system since this variant is commonly used in convenience products and was therefore related to their study of cleaning in a dishwasher. Lang et al. (1991) presented a method for the defined soiling of flat surfaces with commercial starches, while a simple testing method was developed by Gerhards and Schmid (2013) for the investigation of spray cleaning of stainless steel substrates soiled with maize starch.

The origin and processing history of the starch influences its cleaning behaviour. Linderer and Wildbrett (1993) showed that potato starch was easier to clean than maize starches. Many comparative starch cleaning studies have employed wheat starches, as these have sufficiently high resistance to cleaning that differences can be observed in the measurable range. Otto et al. (2016) compared CIP of maize and potato starch based soils and their pre-treatment to investigate the adhesion on a stainless steel surface and showed by measuring streaming potential and isoelectric point (IEP) of acidified or alkalized polymer suspensions before soiling the surfaces, that lower energetic or lower cationic charged soils are easier to clean.

Native maize starch was used by Cerny et al. (2001) in their investigation of a large number of cleaning agents and they reported positive impacts of higher fluid velocity and temperature on removal (which they labelled 'detergency'). Waxy maize starch granules were used by Detry et al. (2011) in their investigation of the adherence of starch aggregates on different substrates. Commercial native maize starch has also been used for extensive research by Jurado-Alameda and co-workers, much using their bath-substrate-flow device (a packed bed through which cleaning fluid is circulated), see Jurado-Alameda et al. (2011a). Jurado-Alameda et al. (2015,2016) compared the effectiveness of different surfactants and an enzyme on soiled glass spheres, polyurethane discs and stainless steel wads. Herrera-Márquez et al. (2019) studied non-ionic surfactants with silica microparticles. Vicaria et al. (2017) investigated ozonation and enzyme recovery under a wide range of operating conditions and cleaning agents, while Vicaria et al. (2018a) and Vicaria et al. (2018b) investigated the cleaning of native maize starch with electrolysed water.

Modified starches are used much more frequently than native starches in the food industry, as these are usually already pre-gelatinised and therefore a homogeneous starch paste can be produced with little effort. This aspect is noteworthy for model soils, since a gelatinisation preparation step, with long inputs of mechanical and thermal energy, could lead to variation of the material properties between different batches of soil samples. Augustin et al. (2010) and Föste et al. (2013) investigated the CIP of a modified waxy maize starch under stationary and pulsed flow conditions in complex geometries on the lab and pilot plant scales.

Other starch types have been employed in cleaning tests. Schöler et al. (2009) used wheat starch in their initial studies of pulsed flow cleaning, while Mauermann et al. (2012) used potato starch as a model soil for the investigation of surface properties and surface roughness of stainless steels on cleaning by water jets.

Starch cleaning tests have prompted a number of cleaning technique developments. Schöler et al. (2012) developed a local optical detection method (Local phosphorescence detection, LPD) using phosphorescent particles in the starch matrix to monitor cleaning. The LPD method was compared with scanning fluid dynamic gauging (sFDG) by Gordon et al. (2014). LPD gave a better indication of the cleaning progress while sFDG provided further insights into the removal mechanisms. Joppa et al. (2017a) and Joppa et al. (2017b) extended the LPD technique and linked their observations to CFD simulations, focussing on pre-wetting and swelling of the soil layer. The results were integrated in a diffusion model for swellable soils (Joppa et al. 2019) and validated by liquid jet cleaning experiments. Fuchs et al. (2017) investigated intermittent liquid jets and compared the results with xanthan gum contaminations of stainless steel plates. Sauk et al. (2018) developed an automated particle analyser for cleaning (APAC) to monitor CIP progress and behaviour in real time. They incorporated laser diffraction particle size measurement with a flow channel cleaning device. Gottschalk et al. (2019) used the APAC system to determine the dominant removal mechanism of particles from a modified waxy maize starch soil layer. As special detection method X-Ray photoelectron spectroscopy was applied by Boyd et al. (2001) to detect the carbon rings of the starch molecules amylase and amylopectin in order to relate their binding energy to the cleanability of a starch soil.

6.2. Other plant-based and microbial hydrocolloids

The term hydrocolloids includes a large group of polysaccharides and proteins that dissolve in water in colloidal form and show a high propensity for gel formation. Almost all hydrocolloids are natural in origin and are widely used in

Table 14 – Overview on composite and other model systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Mustard	5% protein, 10% carbohydrates, 5% fat (Delicato Sennep, Aldi)	Wet soil layer on SS stickes	Direct application	Not specified	Change of steady and unsteady flow, v = 1.0–1.9 m/s	Tap water	Weighing, localisation of maximum residue by optical inspection	Flow rate has no effect on the areas where flow conditions are unfavourable to cleaning	Jensen et al. (2007)
Starch/fat mixture	Potato starch (Panreac), pork lard (El Pozo)	Soft solid layers on SS plates 2.54 × 2.54 cm^2 and spherical fibre coupons Ø 2 cm	Starch gelatinised at 68 °C for 1 h and cooled to room temperature for 1 h; lard heated to below 50 °C and addition of 0.02% Sudan III dye Both components mixed and homogenised	Deposition on plates in a holder with height 1 cm, fibre spheres rolled in mixture	Removal behaviour and CIP Fat/starch proportion 0–100%, Temperature 40–50 °C, pH 3–13.2, time 10–20 min, diff. surfactants	Surfactant, amylase and lipase	Micromanipulation probe and Bath-Substrate-Flow device, weighing, fat-content by spectrophotometry	From strong adhesive and cohesive interactions to reduced cohesive forces for lower starch concentrations, amylase and lipase did not significantly improve cleaning	Herrera-Márquez et al. (2020)
Bread dough	60.6% plain flour, 1.8% wet yeast, 1.2% salt, 36.4% water	Soft solid layer on SS discs Ø 26 mm	Defrosted in a fridge at 4 °C for 12 h	Spreading on discs to a thickness of 2 mm, drying at air	Removal behaviour. Exposure (drying) time 0–40 min	None	Micromanipulation probe	Longer drying requires higher pulling energy	Liu et al. (2006a)
Cake batter	Vanilla cake mix	Baked 'mini cakes' on sample plates 5×5 cm^2 or discs Ø 5 cm of Al alloy, stainless steel uncoated and coated with 7 different fluoropolymers	Mixing with spray dried hen egg and rapeseed oil	Whisking and baking at 180 °C for 8 min, cooled to 22 °C for 30 min resulting in 27% bubbles	Scraping of the soil Lipid content 6.1–20.2 wt%	None	Removal force in a millimanipu-lation device, optical inspection of residues	Little influence of surface roughness, but a strong sensitivity to cake oil content. Adhesion is stronger than cohesion	Magens et al. (2017)
Burned fats, starch, proteins	Whole milk, magarine blend, cheese powder, pasta	Patchy fouling deposit on SS plates 50 × 50 mm^2	Pasta boiled in water, drained and added to the fat emulsion, milk, cheese powder, salt at 50 °C before blending	Wiping blade device giving 300 µm thick, 720 g/m^2 wet coverage. Drying in air at 20 °C for 24 h followed by baking at 204 °C for 7 min	Scraping tests at 20 and 50 °C, pH 5–12, various surfactants and soaking times	NaOH, anionic, cationic and non-ionic surfactants	Millimanipulation removal force, visual inspection	Cohesive and adhesive failure depending on cleaning solution chemistry. Temperature is beneficial for cleaning	Cuckston et al. (2019)
	As above		As above		Initial swelling Various			Delay in swelling due to initial filling	Tsai et al. (2021a)

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– Table 14 (*Continued*)

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Burned fats, starch, proteins		As above, on SS plates $25 \times 100\ mm^2$		Similar to above, giving 400 µm thick layers	surfactants, pH 7–10	Water, surfactants not specified	Layer thickness with sideways fluid dynamic gauging.	of surface cracks. Hysteresis for suction and ejection mode	
Custard	Not specified	Dried soil layer on SS plates $500 \times 500\ mm^2$	Homogenised and heated up to 25 °C	Applied and dried at room temperature for 24 h resulting in a mass of 8.6–11.8 mg/cm^2	Water jet with flat fan nozzle at 2 bar and 22.5 °C for 10 min. Diff. nozzle types, nozzle distance 100–470 mm, flow rate 0.11–1.25 L/min	Water	Cleaned width by fluorescence	Necessary amount of water increases with thicker soil layer	Köhler et al. (2016)
Custard	Not specified	Wet soil layer on SS body and stator of CSPE-based synthetic rubber	12 kg of custard contaminated with 105 CFU/mL *B. cereus* spores	Contaminated custard pumped in in a loop at 60 °C and 300 L/h for 1 h and removed	CIP of a progressive-cavity pump	Water, 0.2% NaOH, 0.2% HNO_3	Counting colonies grown on agar	The method allows the localisation and counting of remaining contamination	Bénézech et al. (2002)
Tooth-paste	Sorbitol, silica, saccharin, titanium dioxide, sodium lauryl sulphate, zinc citrate, water	Soft solid layer on SS, PTFE and glass discs Ø 14 and 15 mm	Untreated	Spreading on discs to a thickness of 0.7 mm	Removal behaviour Gap width, different surface materials	None	Removal force by millimanipulation, adhesion force with AFM	The two methods give comparable results	Akhtar et al. (2010)
Confectionery (Cadbury)	Caramel: glucose, sugar, whey powder, palm oil, water Turkish delight: agar, glucose, starch, sugar, water Sweetened condensed milk (SCM): sugar, butterfat, whey protein, water	As above	Untreated	Layers 0.7 mm thick, SCM baked in oven at 80 °C for 1 h	Removal behaviour Gap width, different surface materials	None	Removal force by millimanipulation device, adhesion force with AFM	The two methods give comparable results	Akhtar et al. (2010)

Table 15 – Examples of related non-food model soil systems.

Soiling					Cleaning				Reference
Material	Composition Product, Supplier	Structure & classification	Production conditions	Soil application	Investigation & varied parameters	Agent	Detection method	Effect & classification	
Glycerine	Not specified	Liquid film on vessel SS wall	Direct unchanged application	Sprayed with spray ball of the CIP system at 20 °C	Contamination of CIP off-stream	Water for injection (WFI)	Online monitoring based on TOC	Method development, proof of concept. Retention time < 10 s, resolution 20 ppm	Siegmann-Hegerfeld et al. (2013)
Synthetic tristearin	Not specified	Wet layer on SS stripes 3.3×32 cm^2	Labelled with carbon-14	Coated to give a thin film	Closed pipe system	0.03 M NaOH	Radioactivity before and after each experiment	Prove of different soil species and description of their kinetics	Bourne and Jennings (1963)
Mineral oil	Atlantic Richfield	Droplets on polyester films	Unchanged or mixed with oleic acid	Application of single 2 µL droplets by micro-syringe and subsequent immersion in water bath	Stirred detergency cell Various surfactants, temperature 25–55 °C	10 nonionic, 2 anionic surfactants	Visual observation	Roll-up and incomplete removal of large oil droplets or marginal roll-up and coarse emulsification observed	Dillan et al. (1979)
Petroleum jelly	Unilever	Viscous soft solid paste on SS, glass and indium tin oxide coated PET discs Ø 50 mm	Petroleum jelly mixed with 5% graphite powder for visual observation	Coating with spatula and sharp blade in a ring with thickness of 0.4 mm and 0.9 mm, stored for > 30 min	Thickness and removal of soil layer Different surface materials	Water	Fluid dynamic gauging in zero discharge mode	Cohesive failure for suction mode for all substrates, but adhesive failure for glass under ejection mode	Yang et al. (2014)
Petroleum jelly	Trilanco White Petroleum Jelly (Poulton-le-Flyde)	Viscous soft solid paste on glass and Perspex plates 300×600 mm^2	Direct application	Coating with slider blade to a thickness of 50–2000 µm	Fixed and moving jet cleaning	Water	Video recording of residual soil in the impact area	The cleaning front has a semi-elliptical shape and can be predicted by theory	Glover et al. (2016)
Petroleum jelly	Roth	Viscous soft solid paste on SS plates	Petroleum jelly mixed with fluorescent tracer Tritec Storelite	Coating with automatically moved doctor blade and dried for 24 h at standard atmosphere conditions	Discontinuous jet cleaning Variation of jet angle 45–90° and gauge pressure	Water	Optical detection of residual soil in the impact area by fluorescence	Calculation of the stress as a function of jet angle	Murcek et al. (2019)
Paraffin	White soft paraffin WSP (Pharmacopoeia)	Soft solid layer on Perspex wall	Direct application	Coating with knife-edge in a tape matrix of 35,000 mm^2 with different thickness	Spray cleaning on a flat plate Flow rate 1–4 L/min. $T = 20$–60 °C. Soil thickness 0.19–1.9 mm	Water for injection (WFI)	Cleaned area *vs.* time by optical inspection	Different cleaning behaviour below and above the drop point of WSP	Rodgers et al. (2019)

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– Table 15 (*Continued*)

Soiling					Cleaning				Reference
Material	**Composition Product, Supplier**	**Structure & classification**	**Production conditions**	**Soil application**	**Investigation & varied parameters**	**Agent**	**Detection method**	**Effect & classification**	
Polyvinyl alcohol	Granules 96% hydrolized, MW 85,000–124,000 kg/kmol (Sigma Aldrich)	Dried gel layer on SS discs Ø 50 mm	Dissolved in RO water at 60 °C with 90 min sonication to give a 2% solution, concentrated to 8% by evaporation	Pouring a layer of 1 mm and drying at 20 °C for 48 h resulting in a film of 80 µm	Swelling $T = 20–30$ °C	RO water	Scanning FDG	Initial swelling of the film is followed by an abrupt detachment Resolution ± 5 µm	Gordon et al. (2010a)
Polystyrene	PSGreen-Fi36 Microparticles GmbH	Spherical monodispersed Ø 1.18 µm particles with FITC marker on SS plates	Direct unchanged application	Sedimentation from aqueous suspension for 24 h	Removal in a flow channel for 2 min. T = 24–70 °C, surface roughness Ra 0.2–2 µm, different weld seams, artificial scratches 200 µm, different surfactants	Tap water, 2 wt% NaOH, 2 wt% H_3PO_4	Counting of fluorescent adherent particles with changing flow rate, 50% criterion for cleaning success	Surfactants have stronger influence than surface properties	Beck et al. (2005)
Polystyrene	Not specified	As above, on different surfaces	Direct application	Sedimentation from aqueous suspension	As above, different coatings	As above, surfactants	As above	Low energy surfaces are easier to clean, surface roughness had no influence on particle adhesion	Bobe et al. (2007)
Silica	Test dust $d_{P,50}$ 3.65 µm	Particulate deposit on metal and polymer discs Ø 70 mm	Suspension of 0.1 g SiO_2 in 3 mL water	Soiling from aqueous suspension and evaporation of the water	Removal by a moving slide simulating swabbing at 22 °C. Roughness Ra 0.2–4.4 µm, water contact angle 62–114°	None	Mobile particle counter	Highest detergency for lower roughness, surface energy is only relevant for polymers	Budelmann and Dreßler (2017)

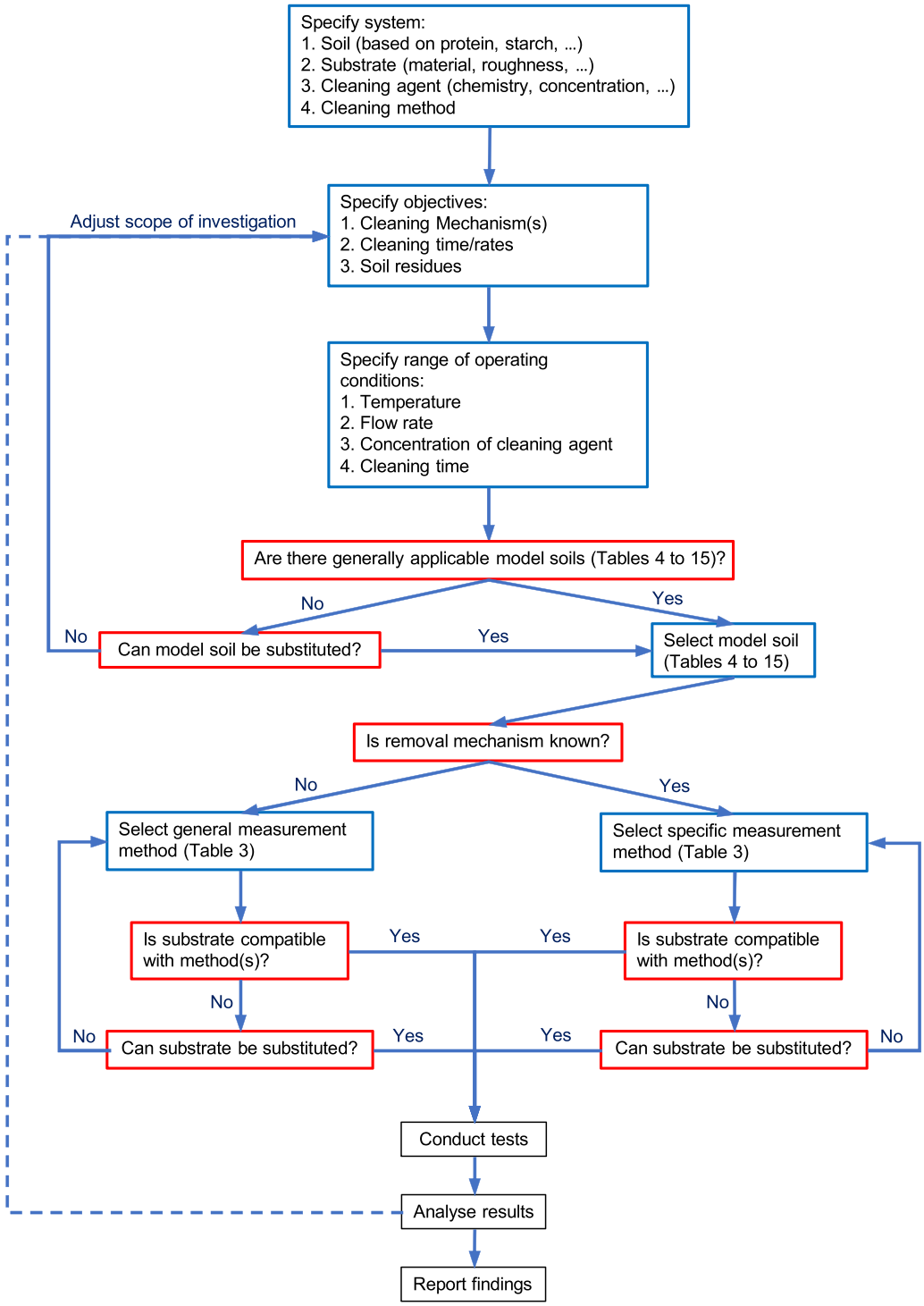

Fig. 5 – Flow chart of decision process in order to find an appropriate model soil for cleaning experiments.

food processing. (Ternes, 2008). Table 9 summarizes model soils of this type.

Xanthan gum is a high molecular weight polysaccharide obtained as a metabolite of the bacterium *Xanthomonas campestris* and consists of a cellulose-like main chain with side chains of mannose, glucuronic acid and pyruvic acid. The molecules are arranged in the form of a double helix and form elongated rods. Xanthan gum is on the E-list of food additives (E415) and is often used in the food industry as a structural improver, thickening and foam agent. Even very low concentrations cause high viscosities in aqueous solutions and exhibit good wall adhesion. The diffusion of Xanthan gum molecules is effectively negligible due to their high molecular mass, so that mass transport processes can be observed without the influence of molecular mass transport. (Ternes, 2008).

Xanthan layers were used by Welchner (1993) to investigate the flushing behaviour of pipe systems with different spatial arrangements and he compared the results with a number of food based soils. Dried Xanthan gum layers containing phosphorescent ZnS particles as an optical tracer were used by Wilson et al. (2015) in their studies of removal of soil layers from stainless steel plates by a moving vertical water jet. The layer exhibited peeling (adhesive failure)

Table 16 – Steps in development of a cleaning study for a food fouling deposit.

Step	Task or activity
1	Conduct chemical analysis of real fouling deposit (*e.g.* carbohydrate, fats, proteins, *etc.*) – check if any compound is disproportionally present in the deposit compared to the process material, and check literature for similar deposits (Tables 5–14).
2	Identify the processing conditions involved in fouling and acquire or develop a fouling apparatus (*e.g.* heat exchanger) for conducting tests under these conditions (Table 2)
3	Identify whether any component is mainly responsible for the appearance of fouling, as they are likely to be those most difficult to remove during cleaning. Note that several fouling processes could occur in parallel, such as mineral (calcium phosphate) and protein deposition in dairy fouling, which individually may require different cleaning protocols.
4	If detailed composition information is available, determine which component(s) are mainly responsible for fouling (*e.g.* in type A dairy fouling, whey proteins are the prime actor despite being present at much lower concentration than caseins).
5	Develop or acquire a cleaning apparatus to conduct general processing test of fouled samples. Implement simple fouling/cleaning monitoring techniques already used in industry (*e.g.* monitoring thermal resistance,Table 3), and ideally a real-time method for monitoring the cleaning solution, particularly for the main fouling ingredient (*e.g.* inline UV-Vis spectroscopy for protein removal, turbidity for particulates).
6	Study standard cleaning process parameters, *i.e.* flow velocity, temperature, cleaning agent type and composition. Identify quantitative trends using cleaning rates or cleaning times, depending on the techniques used. Compare such trends, and the orders or magnitude observed, with real fouling deposits and any simpler soil(s) studied previously, to validate the use of the soil-substrate system. Such empirical studies support cleaning agent selection and initial optimisation of cleaning protocols.
7	If better understanding of the cleaning process is required, a model soil-substrate system should be identified (*e.g.* Fig. 5,Sections 2–4) including any other characteristics found to be important in preliminary studies (*e.g.* rheology, appearance).
8	The cleaning process must be monitored in real-time and preferably *in situ*, in order to obtain quantitative information for the different steps that may occur during the cleaning process. The technique(s) to be used (seeTable 3) will depend on the composition of the deposit, hence general methods (*e.g.* monitoring deposit thickness) are useful to start with.
9	Identify the limiting mechanism(s) that control the cleaning rate, such as chemical reaction, mass transfer, swelling, *etc.* Additional lab scale experiments may be required to study parts of the process in more detail, (seeTables 4–15). Look for factors that support quantitative comparisons, *e.g.* apparent activation energies for the effect of temperature, of mechanism(s) active when cleaning 'Model' or 'Ideal' soils with 'Real' fouling deposits (Table 1).
10	Apply the knowledge gained in steps 7–9 to optimise existing cleaning methods or develop novel cleaning strategies based on the new understanding of the process

rather than erosion. In their investigation of cleaning by pulsed liquid jets, Fuchs et al. (2017) compared the performance of Xanthan gum and starch-based soils on stainless steel plates.

Agarose is a polysaccharide made of D-galactose and 3,6-anhydro-L-galactose. It is the main component of agar and is extracted from certain red seaweeds. Agarose is a powerful gelling agent and responsible for the gelling ability of the agar (Ternes, 2008). It was used by Bobe (2008) to evaluate CIP on stainless steel, PTFE and enamel samples with different surface roughnesses and structure.

6.3. *Sugars*

Sugar is a sweet-tasting, crystalline food which consists mainly of sucrose. Its physical properties, and therefore its cleaning behaviour, are determined by its extent of crystallisation which in turn is controlled by its water content and the temperature. Honey, consisting mainly of the fructose glucose and water, is well-suited for investigated cleaning sugar and other soluble solids. Table 10 records that Welchner (1993) employed glucose syrup to investigate the flushing of pipe systems, while Ali et al. (2015b) used millimanipulation to compare cohesion forces in honey, petroleum jelly, unbaked and baked lard layers.

6.4. *Plant cells and fibres*

The principal components of plant cells are cellulose, hemicellulose, lignin and pectin (Ternes, 2008). In the food sector cleaning problems often arise with plant fibres, which consist of cross-linked plant cells. In some cases, dyes and flavours also cause problems. Table 11 shows examples of models soils of this type. A readily available and often used model plant-derived soil is tomato paste. Tomato paste is made from ripe tomatoes, using only the tomato meat which is pureed and sieved, concentrated under vacuum and heat, and then pasteurized. In addition to water it contains carbohydrates, sugar, proteins, fibres and fats (Ternes, 2008). As a model food soil tomato paste has the advantage that its mechanical properties can be adjusted by heat treatment and hydration. Liu et al. (2002) used baked tomato paste samples to test their micromanipulation technique for measuring the adhesive and cohesive strength of food deposits. They subsequently investigated the effect of surface material, baking and hydration times (Liu et al. 2006b) and soil property distribution (Liu et al. 2006c). A similar paste was used by Chew et al. (2004) to study the effect of baking time on soil strength, and by Saikhwan et al. (2006) to investigate the impact of surface modifications, both using FDG. Hooper et al. (2006a) used tomato paste to compare the millimanipulation and FDG techniques. Tomato paste is viscoplastic and has been used to study the impact of soaking in jet cleaning (Chee and Wilson, 2021).

Other plant-based soils have been used for specific investigations, such as the hop tanning agent concentrate used to mimic flushing of pipe systems in breweries by Welchner (1993). The kinetics of cleaning dried pink guava purée layers were investigated by Khalid et al. (2016) in a new test rig (Khalid et al. 2015) and showed the need for a NaOH cleaning step at higher concentration and temperature, as part of a four step CIP cycle.

7. High-lipid model systems

7.1. Fats

Fats (triglycerides) are esters of the triol glycerol with three, usually different, predominantly even-numbered and unbranched fatty acids. The labels fat and fatty oil refer to whether it is solid or liquid at room temperature. A wide range of fats (animal and vegetable) are used in food processing, reflected in the model systems in Table 12. As natural products, fats are classified as lipids and are soluble in lipophilic organic solvents. Their non-wetting behaviour towards aqueous solutions means that removal either involves melting and displacement (*e.g.* roll-up in Fig. 2) or emulsification and dispersion. Both processes are promoted by surfactants. The wide range of fats means that it can be possible to model cleaning behaviour of a high or low melting point fat at room temperature by careful selection of a proxy material.

Lard has been used as a model soft solid soil by various researchers. Jurado-Alameda et al. (2016) compared the effectiveness of different surfactants for cleaning glass spheres soiled with starch and lard, as well as the impact of an ozonation step (Jurado-Alameda et al. 2012). Ali et al. (2015b) studied the effect of ageing on the cohesive strength of unbaked and baked lard using millimanipulation: this was affected noticeably by the addition of ovalbumin. Tuladhar et al. (2000) tested their fluid dynamic gauging technique for the measurement of the thickness of soft solids using a supermarket butter. Schoenitz et al. (2014,2015) employed carnauba wax nano particles in their investigation of fouling and cleaning of micro structured heat exchangers, and developed an automated local optical inspection system for quantifying the amount of soil present.

Fatty oils such as vegetable-based oils have been used as model mobile soils. Boulangé-Petermann et al. (2006) and Detry et al. (2007) used sunflower oil for their studies of cleaning various surface materials, finishes and coatings by water flows in a laminar flow cells. Welchner (1993) employed a mayonnaise based on soybean oil for his flushing experiments in pipe systems and compared the results with several other food soils. Jurado-Alameda et al. (2011b) used a mixture of pure fatty acids coated on glass spheres to study the effectiveness of surfactants, focusing on different temperatures near the melting point of the acids. Another example is the coconut milk-based fouling layers studied by Saikhwan et al. (2015) and Chutrakul et al. (2018) in fouling and dissolution investigations, respectively.

7.2. Egg yolk

Natural egg yolk consists of approximately 50 wt% water: the other main components are up to 32 wt% lipids and 16 wt% proteins, most of which are present as lipoproteins and small amounts of minerals and carbohydrates (each about 1 wt%) (Ternes, 2008). Table 13 summarizes studies on model egg yolk food soils. Due to the combination of proteins and fats, egg yolk generates a complex soil and is considered to be particularly difficult to clean if dried (Pérez-Mohedano et al. 2017). Soil layer preparation usually involves spraying or spreading a suspension of egg yolk powder in water followed by drying. Baking the layer at temperatures above 80 °C before drying makes it more resistant towards cleaning (Gordon et al. 2012; Helbig et al. 2015).

Helbig et al. (2015) and Deponte et al. (2018) studied cleaning-in-place of egg yolk soil layers prepared as above, using the local phosphorescence method (LPD) for detection. The self-fluorescence of egg yolk meant that tracer particles were not needed, in contrast to starch soils. Gottschalk et al. (2019) determined the size of detached egg yolk fragments at approximately 1 µm. Murcek et al. (2019) studied removal of egg yolk layers by impinging jets and identified the normal and shear stresses required, while Helbig et al. (2019) used a number of methods to quantify soil swelling and changes in soil material properties.

Egg yolk soils can also be obtained as standard soils from the Centre for Testmaterials in Vlaardingen, Netherlands. Gordon et al. (2012) investigated the influence of enzymes on the swelling of this standard soil while Pérez-Mohedano et al. (2015,2017) have measured and modelled the cleaning of egg yolk soiled surfaces in a dishwasher.

8. Composite and other soil systems

More complex model systems are used to give a better representation of a real food system, but this can limit the transfer of results to other, related, systems. Further issues associated with composite soils are complex production, handling and reproducibility. This notwithstanding, a number of composite soils have been used to good effect, see Table 14.

One example is mustard, which is made from the ground seeds of white, brown and black mustard mixed with water, vinegar and salt. It therefore contains water, carbohydrates, proteins and fats. Jensen et al. (2007) used a mustard coating to study cleaning induced by steady and unsteady flow velocities in difficult-to-clean areas. Herrera-Márquez et al. (2020) employed starch/fat mixtures with different concentrations on stainless steel plates and fibre spheres in developing cleaning maps. A commercial custard was used by Köhler et al. (2016) in their study on jet parameters in jet cleaning of stainless steel surface, while a similar material was used by Bénézech et al. (2002) to develop a test method in which bacterial contamination was used to detect food-based residuals.

Even closer to reality but very specific in application are convenience foods or ready-mix products. Liu et al. (2006b) measured the adhesive or cohesive strength of a frozen bread dough. Magens et al. (2017) baked 'mini cakes' on coated surfaces to investigate the effect of formulation and surface characteristics on adhesion forces. Cuckston et al. (2019), and Tsai et al. (2021a) used a baked pasta and cheese slurry to simulate burnt-on baked-on food deposits and study the effect of surfactants, pH, temperature and soaking time on the removal. Akhtar et al. (2010) compared micromanipulation and atomic force microscopy (AFM) measurements of adhesion for a number of products including toothpaste and confectionery soils. The noteworthy feature of these studies on complex soils which differentiated them from empirical studies, *e.g.* 'test and look', is that the experiments were accompanied by direct measurement of attributes of the soil, whether thickness or strength, in addition to any visual measurements, to give mechanistic insight into the removal process.

Several standard soils are based on composite soils. An example is the DIN EN 60436 standard for the evaluation of dishwashers for domestic use. This covers the range of typical soils found on cook- and tableware, including raw

materials like milk, tea, egg yolk and margarine and more complex food stuffs like minced meat mixed with egg, porridge cooked with milk and water, as well as chopped spinach with margarine. The common dish materials glass, ceramics, melamine, metal are employed. These standard soils are not included in Tables 2 and 14.

9. Non-food model systems

Some of the model soils used to investigate cleaning mechanisms, while not foodstuffs, behave similarly to some food systems and are recorded in Table 15 here as potential alternatives. They could also be used to represent pharmaceutical systems.

Particulate deposits were used by Beck et al. (2005) and Bobe et al. (2007) in fundamental investigations on the adhesion of single polystyrene particles on machined stainless steel surfaces, while Budelmann and Dreßler (2017) evaluated the cleanability of open surfaces using soils generated from aqueous suspension of silica.

Siegmann-Hegerfeld et al. (2013) contaminated a vessel with glycerine to investigate a novel TOC based online monitoring system for CIP processes. Bourne and Jennings (1963) used a synthetic tristearin labelled with carbon-14 to determine cleaning kinetics. Dillan et al. (1979) studied cleaning of individual droplets of a commercial white oil (a mineral fatty soil) on polyester films when comparing surfactants. Gordon et al. (2010a) used dried films of polyvinyl alcohol on stainless steel discs to study swelling and detachment mechanisms similar to those seen with gelatine and alkali cleaning of proteinaceous soils.

Petroleum jelly and paraffin waxes are viscoplastic (Fernandes et al. 2021), as are many difficult to remove soiling layers. These have been used in studies of impinging jet cleaning *e.g.* Glover et al. (2016), Murcek et al. (2019), and spray cleaning (Rodgers et al. 2019).

10. Guidance for selection of model soils

The above sections have established that food soil-surface systems are complex owing to the multicomponent and often multiphase nature of many foods. Selection of a suitable soil-surface system to provide mechanistic insight and quantitative information for designing, modelling or optimising cleaning operations is likely to involve some iteration. Fig. 5 is a flowchart outlining the decision process involved in selecting a suitable model system. Table 16 describes the sequence of steps, which an experimental study may follow, starting with an empirical investigation to establish the key parameters involved in a particular cleaning application and develop the focus of a model study.

11. Conclusions

The underlying complexity of food materials means that fouling deposits and other food soils are often multiphase and heterogeneous. The need to identify and understand the mechanisms involved in cleaning has prompted the use of model soil-surface systems for use in systematic experimental investigations at the laboratory scale. This review has classified the model soils used to date in terms of primary composition, subject to the understanding that many soils are composite in nature and some of the complexity arises from interactions between different components.

Selection of an appropriate food soil-surface system must balance the ability to mimic the real process, *i.e.* not oversimplifying the system or geometry, against the requirements of the measurement or monitoring technique and the resources (time, volumes *etc.*) available. The complexity and subtlety of contributions from substrate composition and topography factors means that experimental systems have tended to employ substrates representative of those employed in industrial practice. The range of instruments and sensors available to make *in-situ* measurements in real time continues to grow. Some of these have been developed specifically to tackle the challenges associated with food soils, while others have been developed in related sectors (*e.g.* for membrane and biofilm applications).

A spectrum exists between ideal soils, which can be described by mathematical equations based on fundamental principles, and real soils, which support empirical relationships, as discussed by Wilson et al. (2022).

The main advantage of model soils is that hypotheses of the cleaning process can be tested and experimented in a simple, reliable and systematic manner. This is particularly relevant when such questions relate to the soil deposits themselves, *e.g.* its composition, structure, ageing, chemical interactions, *etc.* Model deposits are much more versatile to create, and thus test in cleaning experiments. Moreover, the type of model deposit to consider may depend on type of question to answer. For example, the explanation behind the optimum caustic concentration in dairy deposits was finally obtained using soluble whey protein aggregates (Fan et al. 2019a), a far cry from real milk fouling.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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