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Legge, A. orcid.org/0000-0001-7930-2471, Nichols, A. orcid.org/0000-0003-2821-621X, Jensen, H. et al. (2 more authors) (2021) The characteristics and in-sewer transport potential of solids derived from domestic food waste disposers. Water Science and Technology, 83 (12). pp. 2963-2979. ISSN 0273-1223

https://doi.org/10.2166/wst.2021.169

The characteristics and in-sewer transport potential of solids derived from domestic food waste disposers

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ABSTRACT

This study aims to assess the transportability of food waste disposer particles within a sewer system. A series of laboratory studies has examined the physical characteristics of solid particles derived from domestic food waste disposers. Particle size distributions and maximum settling velocity characteristics were measured for 18 common food types, and stored in a publicly accessible database. Particle size distributions are shown to fit well with a 2-parameter Gamma distribution. Settling velocity is generally higher for larger particles, except when particle density and sphericity change. For most food types, particle specific gravity was close to unity. Egg shell particles had a significantly higher specific gravity. This information, combined with the particle size data have been used to show that there is a very low likelihood of food waste particle deposition in sewers during normal operational flows, other than temporary transient deposits of egg shell particles.

Key words | domestic food waste disposers, food waste, in-sewer deposition, particle fall velocity, sewer solid entrainment thresholds

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HIGHLIGHTS

- Particles characterised for 18 common food types.
- Sizes fit a Gamma distribution, mode of 0.59 to 4.76 mm.
- Most particles had apparent densities close to water.
- Most particles entrained at low boundary shear stress, unlikely to form deposits in sewer pipes.
- Egg shell showed higher entrainment threshold, but still expected to transport during dry weather flows.

INTRODUCTION

There is considerable debate on the best way to manage the disposal of unavoidable domestic food waste, and there is no clear consensus on the optimum approach (e.g. Schanes *et al.* 2018; Slorach *et al.* 2020). In England, the food waste of more than half of households (54%) is still collected with other solid waste by centralised municipal collection and disposal (WRAP 2015). In Europe, Member States are required to encourage householders to separate out their average 173 kg food waste per person per year (Schinkel 2019) for home composting or kerbside collection (EU Amending Waste Framework Directive 2018, Article 22). However, the effectiveness of this approach has been found to be limited to less than 50% of separable food waste (e.g. STOWA 2015). There are also concerns regarding the overall carbon emissions from kerbside collection. In England kerbside collection is seen as the recommended way forward for all domestic food waste by 2023 (Defra Environment Bill 2020), with resource recovery achieved

doi: 10.2166/wst.2021.169

primarily via municipal authority street collection trucked to dedicated anaerobic digestion (AD) plants. It is recognised that this approach will require considerable investment in vehicles and digestion plants and may also not provide the minimised carbon emissions compared with other waste management options (e.g. Jenkinson 2020).

In a number of regions around the world, food waste is disposed of by discharging it into the wastewater collection system after processing using domestic food waste disposers (mechanical grinders) that break down food into small particles, e.g. in Surahammar, Sweden (Evans *et al.* 2010). More than 50% of households in the USA have food waste disposers (American Housing Survey 2013), in excess of 34% of households in New Zealand, and 10% in Canada. In the EU, fewer food waste disposers (FWD) are generally in use, with only 5% of households evidenced in the UK (Iacovidou *et al.* 2012). However, there are various initiatives investigating how FWDs can be used to enable householders to separate their food waste at source to enable resource recovery (e.g. Bisschops *et al.* 2019; Run4Life 2020). This shift in domestic food 'waste' as part of wastewater inputs to wastewater treatment plants (WWTPs) becoming seen as a potential resource, has come about due to recent concepts such as the circular economy and the need to better manage carbon (Skambraks *et al.* 2017; van Leeuwen *et al.* 2018; Velenturf *et al.* 2018; Sancho *et al.* 2019).

Although FWDs have been used in domestic kitchens since the 1920s (Atwater 1947), their effectiveness at grinding domestic food wastes into particles that can be reliably conveyed in sewers has been studied rarely. Although some earlier studies were concerned with the implications for solids conveyance and transformation (e.g. Jones 1990), few have considered the physical characteristics and transport mechanics of FWD particles in sewer networks. Many objections to FWD use are based on anecdotal observations rather than objective, testable data, for example, recent studies such as Thomsen *et al.* (2018), the EU DECISIVE project, asserted that ground food introduced to sewers leads to unspecified 'damage' and 'risk' but without providing supporting evidence.

There is only very limited information about how FWD solids move in sewer networks, their deposition likelihood, and their re-entrainment potential. This study aims to assess the transportability of food waste disposer particles within a sewer system.

Sewer solids transport and FWD particles

The variety and range of solids entering, depositing and moving in sewers are broad (Ashley *et al.* 2004). Where there are sanitary sewers separate from stormwater collection systems, the solids are comprised of domestic, commercial and industrial inputs (e.g. Alda-Vidal *et al.* 2020). Increased used of FWDs could result in food waste comprising a significant organic load input to sanitary sewers.

Settling and transport of solids by turbulent flows are dependent primarily on particle and flow characteristics. The particle characteristics include particle diameter (d), density (ρ_s) and shape. Equation (1) reflects the balance between flow and particle characteristics. In this, w is the particle settling velocity and u^* is the boundary shear velocity, given by Equation (2), for which τ is the boundary shear stress and ρ is the fluid density. This reflects the ability of turbulent flows to transport solids, while the particle settling velocity reflects the ability of the solid particle to settle, incorporating particle size, density and shape in a single parameter (Breusers & Raudkivi 1991):

$$\xi = w/u^* \tag{1}$$

$$u^* = \sqrt{\frac{\tau}{\rho}} \tag{2}$$

Equation (1) presents the sedimentation parameter, ξ, which reflects the balance between fluid mobilising forces and the inertia of solid particles. According to Breusers & Raudkivi (1991), particles in a turbulent flowing fluid would be expected to settle onto the bed when $\xi > 6$ or to move along the bed as bedload when $6 > \xi > 2$. Below 2, particles will move either in suspension or by intermittent contact with the bed. However, the ranges of this non-dimensional ratio have been determined from observations of granular particles with high sphericity, and while indicative of the potential movement of organic particles of low density, investigation is required to confirm these thresholds for low density, irregularly shaped food particles.

Numerous studies have determined that the particle size of wastewater derived organic solids conveyed in sewers are <0.1 mm (e.g. Levine *et al.* 1985; Ashley *et al.* 2004) and that the settling velocities of these particles vary widely. For example, Pisano (1996) gives a range from 0.001 to 1 cm/s for all particles conveyed in dry weather flow from samples in the USA and Canada. Michelbach & Whorle (1992) determined settling velocities for particles in dry weather flows for 55 sites in Germany as ranging from 0.01 cm/s to 8.7 cm/s. Given the wide range of organic solids already present, FWD inputs may not substantially change the composition, but the relative impact of FWD inputs have not generally been considered, thus a robust investigation is needed to characterise the properties of FWD derived solids specifically.

The American Society of Sanitary Engineering (ASSE 2019) provides performance requirements for food waste disposers, primarily that particles no greater than 12.7 mm should discharge from the device, and particles greater than 6.4 mm should comprise less than 6.25% of the input load. This was specifically for a 454 g food mix comprised of steer ribs, carrots, celery and lettuce in equal proportions. The Association of Home Appliance Manufacturers (AHAM 2009) provided a more detailed protocol for testing, using the same food mix. They suggest using a sieve stack to characterise the spread of particle sizes between 0.425 mm, 2.360 mm, 6.350 mm and 12.700 mm sieves, based on the standard phi scale.

Previous studies on FWD-derived solids have used sieve testing to determine particle size, but without a consistent sieve stack, consistent procedure, or consistent food mix. Therefore comparisons of results for the characteristics of FWD derived solids is problematic. Kegebein *et al.* (2001) used six sieve sizes and considered 16 foods (some mixed), and also the settling behaviour of food mixes. Most particles were smaller than 2 mm and the settling velocity was up to around 0.06 m/s. Galil & Shpiner (2001) used five sieve sizes to examine unspecified food mixes from FWDs with different grind speeds to determine that most particles were <2.9 mm in size and that 'scouring' velocities were from 0.5 m/s for the lightest particles up to 0.84 m/s for some particles of egg shell and bone (although it was noted that this high scour velocity could correspond to only a 'very small part of the ground material'). These results were based on an adjusted Camp's formula (Equation (3)) using particle relative densities (by comparing with sucrose solutions of known density), of 1.0 to 1.1 for 'ordinary basket' particles (no egg shell or bone) and up to 2.3 for bones and egg shell:

$$Vc = \frac{1.486}{n} R^{\frac{1}{6}} \sqrt{B(Sp-1)d} \tag{3}$$

In Equation (3), Vc is the scouring velocity in m/s; Sp relative particle density; d particle diameter; n Manning's roughness coefficient; R hydraulic radius; B is a non-dimensional coefficient related to particle type (0.04 for initiation of movement of granular particles; 0.06 for 'sticky' particles; 0.8 for fine cleaning of sewer). $B = 0.06$ was used in the calculations for the 'ordinary basket' particles and even with a range of sewer sizes (up to 800 mm) and relative flow depths (from 0.25 to 0.75), the particles were found to be conveyed at velocities as low as 0.5 m/s. These findings indicated that FWD solids will mainly be transported without deposition in the sewers considered in the study. However, the denser particles, including ground egg shells (2,241 kg/m^3) were found likely to deposit temporarily during low flow periods, as found by Mattsson *et al.* (2014).

Channon *et al.* (2013) used food mixes and five types of FWD, with only two sieve sizes, to show that most emitted particles were <4 mm in size, although there were variations in the results depending upon the type of FWD used. Drinkwater *et al.* (2015) used only three sieve sizes to determine that most FWD particles were <5.6 mm in size. In these studies, it was claimed that FWD solids could lead to blockage problems if input to sewer networks, while the other studies mentioned above suggested the heaviest FWD particles would only temporarily deposit before being scoured during the peaks of dry weather flows.

Critically, the literature described above provides little means to predict deposition risk of FWD derived particles in sewer systems. This paper reports on work designed to determine the physical nature of FWD derived solids, using a repeatable and rigorous set of tests, to address the question as to when, where and how FWD derived solids can be conveyed or deposited in sewer networks.

Objectives

A key knowledge gap in the assessment of the use of FWD is the risk associated with using conventional wastewater collection systems (sewers) as the transport conduit for the ground solids. There have been a number of individual observations in the field that FWD particles can deposit in sewer systems and possibly create problems as outlined above (e.g. Mattsson *et al.* 2014; Drinkwater *et al.* 2015). In the study reported here the intention was to establish an experimental protocol to collect high quality (repeatable) particle characterisation data in order to determine when there may be an in-sewer deposition risk from FWD particles.

Laboratory measurements are described which aimed to determine the physical size and fall velocity distributions of FWD derived particles for a wide range of food types. The food types selected were the more common components of food mixes currently found in the UK and USA, so that the impact of individual food type characteristics on representative particle mixtures may be examined.

MATERIALS AND METHODS

Food types and food mixes

This study considers the term 'food type' to represent an individual food (e.g. carrot) while 'food group' refers to the broader category (e.g. vegetables). The study aimed to characterise a range of common food types (e.g. potato, onion and carrot) spanning several food groups, e.g. vegetables and fruit. FWD particles from these different food types were expected to exhibit a variable range of physical characteristics.

The study has used published data for food waste generation in UK households (WRAP 2009), and US households (Kim *et al.* 2015) to select a range of foods for study. Table 1 shows the typical overall composition of food waste (henceforth referred to as a 'food waste mix') in the UK (WRAP 2009) and in the USA (Kim *et al.* 2015). This shows that: (i) many of the same food types appear in both mixes; (ii) there are substantial differences in the proportions of individual foods; (iii) different food groupings are used in the UK and USA.

The present study characterised 18 different solid food types shown to be significant in UK and US diets in Table 1 (indicated by *). These food types span all major food groups. The food types examined in this study are shown in Table 2, and were selected to provide a range of common foods found in both UK and US food mixes and that were expected to demonstrate a range of different properties when processed by FWD. Foods were raw unless otherwise stated in Table 2. Beef and chicken were purchased in cooked form, while pasta and rice were cooked according to manufacturer instructions.

Experimental overview

The experimental work was undertaken in several stages – (i) initial food processing; (ii) particle size characterisation; (iii) measurement of particle settling velocity; (iv) examination of re-entrainment of particles most likely to settle.

The primary equipment is shown in Figure 1, comprised of a FWD linked to a sealed unit to collect all the food particles, a water supply, a set of calibrated, graduated sieves, and a 290 mm diameter 1,293 mm length settling column.

All aspects of the particle measurement and characterisation took place on the same working day for each sample of ground food waste to ensure that the particles did not degrade between the different measurements. A detailed measurement protocol was followed according to the laboratory procedure described in detail by Nichols *et al.* (2020), and is summarised here. The entire process (from initial food processing to particle size and fall velocity measurement) was repeated three times for each food type to quantify experimental variability and the data were then averaged.

Initial food processing

Food samples were obtained from a standard commercial source (Table 2) and stored according to the supplier

Table 1 | UK and US food waste mixes, groups and types (WRAP 2009; Kim *et al.* 2015)

UK food waste mix (WRAP 2009)

Vegetables (38%)		**Bakery (16%)**	
Potato*	40.1%	Bread*	82.5%
Mixed	13.0%	Speciality	10.1%
Onion	6.8%	Morning bread	1.9%
Carrot*	6.2%	Other	5.5%
Cabbage*	4.4%	*Characterised	82.5%
Lettuce	3.5%	Scale factor	1.21
Tomato	33%	Meat/Fish (12%)	
Roots	2.5%	Poulty*	48.8%
Cucumber	2.3%	Pork	19.5%
Corn	22%	Fish*	7.0%
Broccoli*	2.1%	Lamb	5.2%
Cauliflower	2.1%	Other*	19.5%
Salad	1.9%	*Characterised	75.3%
Bean	1.5%	Scale factor	1,33
Pepper	1.2%	Processed vegetables (4%)	
Leek	1.0%	Potato*	36.3%
Mushroom	0.8%	Slaw/humus	14.7%
Spring onion	0.4%	Other	49.0%
Other	4.5%	*Characterised	36.3%
*Characterised	52.9%	Scale factor	2.76
Scale factor	1.89	Staples (4%)	
Fruit (22%)		Cereal*	36.8%
Banana	28.5%	Rice*	31.4%
Apple*	23.9%	Pasta*	20.6%
Orange*	12.0%	Flour	0.0%

(*continued*)

Table 1 | continued

UK food waste mix (WRAP 2009)

Melon	9.2%	Other	11.3%
Stone fruit	6.2%	*Characterised	88.7%
Other citrus	4.1%	Scale factor	1.13
Bernes	4.1%	Dairy/Eggs (3%)	
Other	12.0%	Egg shell*	38.6%
*Characterised	35.9%	Cheese*	27.1%
Scale factor	2.78	Egg	17.1%
		Other	17.1%
		*Characterised	65.7%
		Scale factor	1.52

US food waste mix (Kim *et al.* ⊠⊠⊠⊠)

Fruit 37%)		Grains (21%)	
Grapefruit	31.3%	Spaghetti	222%
Banana peel	15.6%	Mac & cheese	16.7%
Watermelon	15.6%	Rice, cooked*	16.7%
Pineapple*	12.5%	Corn flakes*	11.1%
Apple*	9.4%	Cheerios	11.1%
Orange peel*	9.4%	Bread, white*	11.1%
Cantaloupe	6.3%	Sugar	11.1%
*Characterised	31.3%	*Characterised	38.9%
Scale factor	3.20	Scale factor	257
Vegetables (28%)		Meat (9%)	
Cabbage*	24.5%	Beef*	40 0%
Potato*	22.4%	Pork	26.7%
Lettuce	16.3%	Raw chicken skin	20 0%
Broccoli*	12.2%	Hot dog	13.3%
Carrot*	8.2%	*Characterised	40 0%
Celery*	8.2%	Scale factor	2.50
Cucumber	4.1%	Dairy (6%)	
Pepper	4.1%	Cheese*	40.0%
*Characterised	75.5%	Cottage cheese	40 0%
Scale factor	1.32	Butter	20.0%
		*Characterised	40 0%
		Scale factor	2.50

Percentages are of unprocessed (not dried) food waste by mass. Percentages of food groups (e.g. vegetables) indicate the proportion of each food mix (UK or US), while percentages of food items (e.g. potato) indicate their proportion within each food group. The percentage characterised indicates the proportion of each food group characterised in this study, and the scale factor is thus used to scale the results to represent the whole group.

instructions. Food was prepared by cutting into pieces small enough to fit into the FWD unit (3–4 cm approximately in each dimension). Foods were prepared in samples of around 500 g (±5% as per AHAM 2009), with the exact mass of each sample being recorded. Egg shells were mostly in a halved state (not crushed), and were rinsed before being introduced to the FWD.

The FWD used was an Insinkerator Evolution 100-1B (serial number 16093104329). The same FWD unit was used for all food types. The water supply to the FWD was turned on and supplied a constant flow of 0.17 l/s. Water was always below 27 °C (AHAM 2009). The entire 500 g (±5%) food sample was added into the FWD. The water supply was maintained until no visible particles could be seen exiting the disposer. This period lasted around 50–60 seconds in all tests for this constant flow rate. Any variation in water used between tests did not appear to link to food type.

The mixture of water and food particles exiting the disposer was collected in a clean and dry laboratory container.

Measurement of particle size distribution

The purpose of this measurement was to determine the mass proportion of the original food sample ground into certain sieve size fractions. A stack of sieves was used according to BS ISO 3310-1:2016 and BS ISO 3310-2:2013 to characterise the particle size distribution. The sieve sizes used ranged from -3ϕ to $+4\phi$ and were arranged in 0.5ϕ increments (where sieve size in mm is given by $2^{-\phi}$, and thus ranged from 0.06 mm to 8.00 mm). This provides a broader range and higher resolution than that suggested in the AHAM (2009) protocol. The water and particle mixture collected from the FWD was stirred to fully suspend the particles and tipped smoothly into the top of the sieve stack, ensuring all of the particles were emptied from the container, undamaged by rinsing.

Beginning with the top sieve, a small water flow was used to gently wash particles through into the next sieve if they were smaller than the sieve size, without visibly damaging the particles. This was repeated sieve by sieve, down the stack, spending at least 5 minutes on each sieve to ensure all particles smaller than the sieve size were carefully washed through. Once the particles had been separated on the sieves, the sieves had the excess water removed by firmly tapping them one-by-one repeatedly above a sink until no more excess water was being released. Each sieve (including the particles) was then weighed using a calibrated electronic balance, with a resolution of 0.1 g.

Table 2 | Food types used in this study

Food type	UK food group	US food group	Details	Brand
Apple	Fruit	Fruit	Pink Lady	Tesco
Beef	Meat/fish	Meat	Cooked slices	Tesco Finest
Broccoli stem	Vegetables	Vegetables	Pre-packed	Tesco
Cabbage	Vegetables	Vegetables	Sweetheart	Tesco
Carrot	Vegetables	Vegetables	Batons	Tesco
Celery	Vegetables	Vegetables	–	Tesco
Cheese	Dairy/eggs	Dairy	Mature Cheddar	Cathedral City
Chicken carcass	Meat/fish	–	Pre-cooked, meat removed	Tesco
Cornflakes	Staples	Grains	–	Kellogg's
Egg shell	Dairy/eggs	–	Chicken eggs	Various
Orange peel	Fruit	Fruit	Cambria Naval	Tesco
Pasta	Staples	–	Fresh penne (cooked)	Tesco
Pineapple	Fruit	Fruit	Costa-Rica	Co-op
Potato	Vegetables	Vegetables	Maris Piper	Tesco
Rice	Staples	Grains	Basmati pouch (cooked)	Tilda
Sunflower seeds	–	–	–	Tesco
White bread	Bakery	Grains	Toastie	Warburton's
Whole mackerel	Meat/fish	–	Gutted	Independent fishmonger

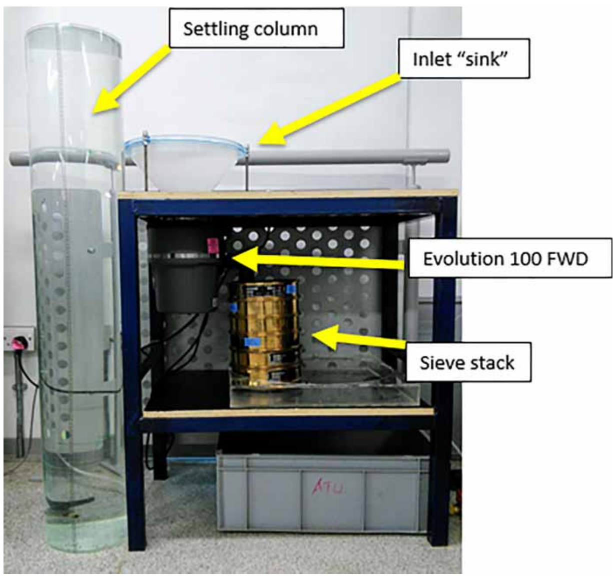

Figure 1 | Laboratory equipment – for the testing of an Evolution 100 Food Waste Disposer.

Particles were collected from the sieves to be used in the particle settling velocity measurement, and the sieves were thoroughly washed. The wet sieves were then tapped again to remove excess water, and were weighed (without particles). The wet sieve mass was subtracted from the wet sieve mass with particles to give the mass of wet particles collected in each sieve. The proportion in each sieve was calculated as the ratio of the wet food mass in each sieve to the total wet food mass across all sieves multiplied by 100%, following the AHAM (2009) protocol. This process was repeated three times for each sample for each food type and averaged, again according to AHAM (2009).

Settling velocity

The maximum settling velocity of the food particles within each sieve size fraction for each food type was measured. This provided the information needed to determine the likelihood of those particles settling within a sewer flow (Equation (1)). Here, 2 g samples of food particles were taken from each sieve, mixed carefully to ensure uniformity. The 2 g sample was mixed with 15 ml of water to form a suspension before being carefully tipped into the centre of the 295 mm diameter settling column's water surface, without giving the food particles any initial vertical velocity. Settling time was recorded at regular intervals throughout the 1,293 m long column to determine the point at which a stable terminal velocity was reached. For all foods, terminal velocity occurred by 385 mm below the water level. The time taken for the fastest falling particle to travel a distance of 710 mm below this height was recorded. The fastest falling particle within each size fraction was tracked as it represented the greatest settling velocity. The settling velocity of each size fraction for each of the food types was measured three times to assess variability and then averaged. The maximum settling velocity reported was therefore an average of three separate measurements.

Particle entrainment

As both the particle size distribution (psd) and the fall velocity distribution by mass fraction had been obtained from all the food groups it was possible to estimate the solid density of particles of a particular size fraction. This was done to estimate the boundary shear stress at the threshold of motion. The size fraction through which 95% of the mass is finer (d_{95}) was selected as the practical maximum particle size for the ground food waste of each food group. Once this was calculated by interpolation of the psd data, the fall velocity for that particle size (V_{95}) was also estimated by interpolation of the fall velocity data. The Reynolds Number ($Re = \rho V_{95} d_{95}/\mu$, where μ is dynamic viscosity of the fluid) associated with the size faction d_{95} was calculated and this was used to estimate the drag coefficient C_D using Equation (4) (Barati *et al.* 2014). Once this had been obtained then the solid density of the ground food waste (ρ_s) for the d_{95} size fraction could be obtained using Equation (5) (force balance equation for a sphere falling in a fluid at terminal velocity). Both Equations (4) and (5) assume that the particles are spherical in shape:

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34 \tag{4}$$

$$\rho_s = \left[\frac{3V_{95}^2 C_D \rho}{4gd_{95}}\right] + \rho \tag{5}$$

Egg shell was identified by previous field studies (Mattsson *et al.* 2014) as a food type more likely to settle within sewers. Given the higher particle density and the irregular shape of egg shell particles, additional experiments were carried out to better ascertain the shear stress required to mobilise deposited egg shell particles as a function of their size, density and the ambient flow conditions. The results were then used to determine the equivalent spherical particles with similar behaviour, as used in conventional threshold of particle motion relationships.

An erosion meter based on the design of Liem *et al.* (1997) was used. First, a shear stress calibration was performed using sands of different sieve sizes, and the frequency of rotation at the threshold of motion for each size was determined, so that a bed shear could be estimated with a fixed value of Shields' number, as given in Equation (6):

$$\Theta = \frac{\tau_c}{(\rho_s - \rho)gd} \tag{6}$$

where Θ is the Shields' number, τ_c the critical shear stress, ρ_s is the particle density, ρ is the fluid density, g is the acceleration due to gravity, and d is the particle diameter. This follows the methodology described in Seco *et al.* (2014). This procedure enabled a linear fit to characterise the relationship between the angular velocity of the propeller and bed shear stress:

$$\tau = 0.075\omega - 1.055 \tag{7}$$

where ω is the angular velocity of the propeller in revolutions per minute. This expression fitted the data with a coefficient of determination of 0.995. The expression was used to determine the applied bed shear stress at the threshold of motion for egg shell particles based on the measured angular propeller velocity.

Egg shells were processed using the FWD according to the method described in the 'Initial food processing' section. The shell particles were sieved into nine size fractions ranging from 0.16 mm to 4.5 mm. For each size fraction, a sample was collected and placed in the base of the erosion meter such that an even bed was formed with the surface of the egg shell deposit 30 mm below the propeller. The angular velocity of the propeller was increased from zero in increments of one revolution per minute (RPM) until sustained motion of particles was observed (taken as several particles in motion at all times). Equation (7) was used to convert this angular velocity into a shear stress for the egg shell particles at the threshold of motion. Measurements using the egg shells were repeated twice for each size fraction to quantify a representative average and assess experimental variability.

RESULTS

Particle size distribution

Figure 2 shows the particle size distributions by mass on a phi scale for all 18 food types tested. Figure 3 presents the cumulative mass distribution. In both figures error bars represent standard deviation observed for the repeated

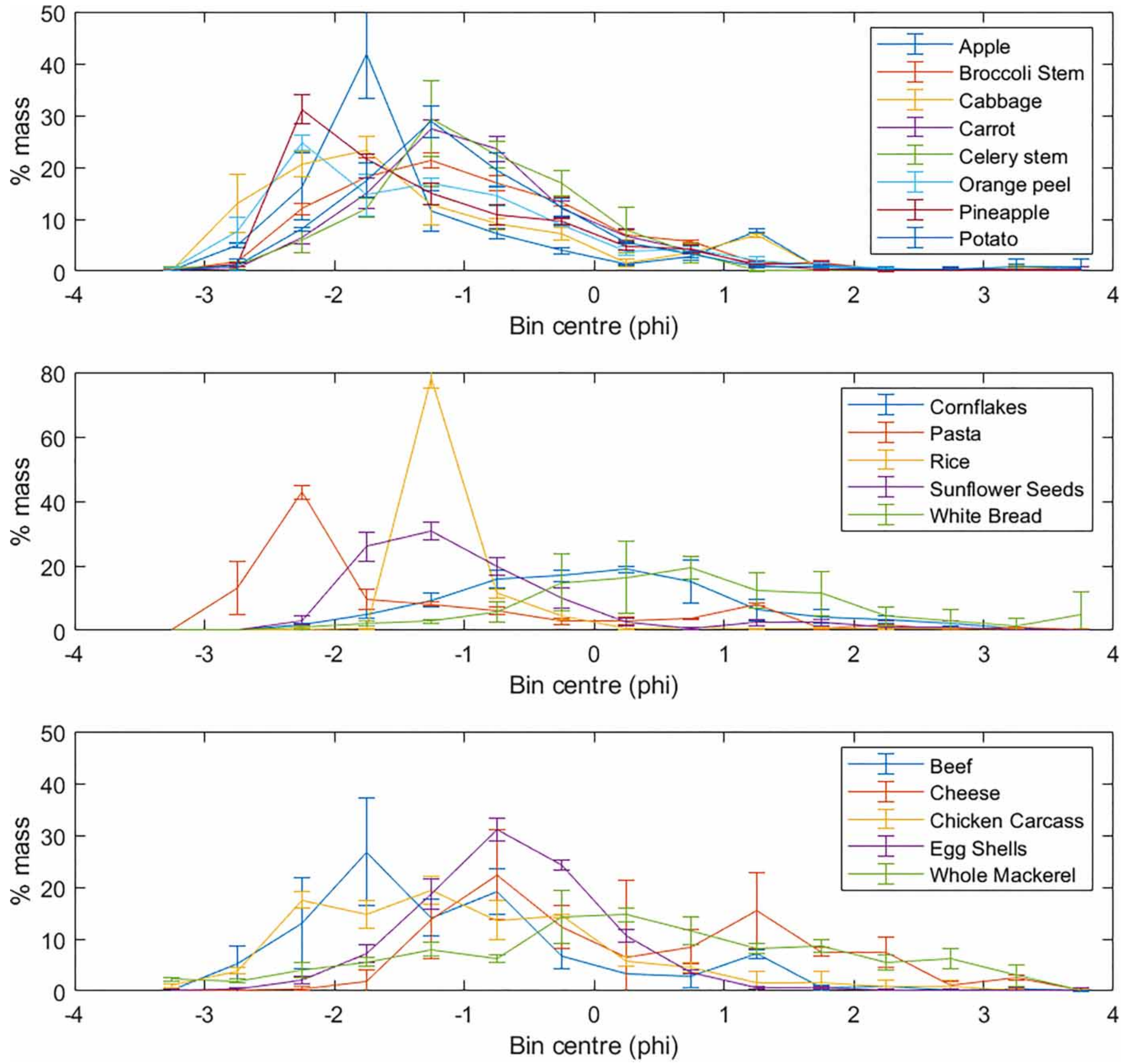

Figure 2 | Particle size distribution for 18 food types: (top) vegetables & fruit; (middle) bakery & staples; (3) meat/fish & dairy/eggs. Error bars represent standard deviation from repeated measurements.

measurements. The phi scale is a logarithmic scale that enables more nuanced inspection of trends for the finer particles. It is a standard scale for measurement and interpretation of sewer solids. The phi unit is calculated from the sieve opening size in mm in Equation (8):

$$phi = log_2(d) \tag{8}$$

So, a small phi value indicates a large sieve size (e.g. $-3\text{phi} = 8$ mm) and a large phi value indicates a small sieve size (e.g. $4\text{phi} = 0.0625$ mm). The bin centre on the horizontal axis is the centre of the size range captured by each sieve, in units of phi. Figure 2 shows that the particle size distributions were generally unimodal and demonstrated a wide range of sizes. For the 18 food types measured, the modal particle size occurred in the range of 0.59 mm to 4.76 mm. The mean particle size of each distribution ranged from 0.58 mm to 2.70 mm. The narrowest size distribution was for rice, which showed a much more prominent mode (most common size fraction), as the rice particles were already close to this modal size when entering the FWD. The width of each distribution is quantified via the standard deviation, as shown in Table 3.

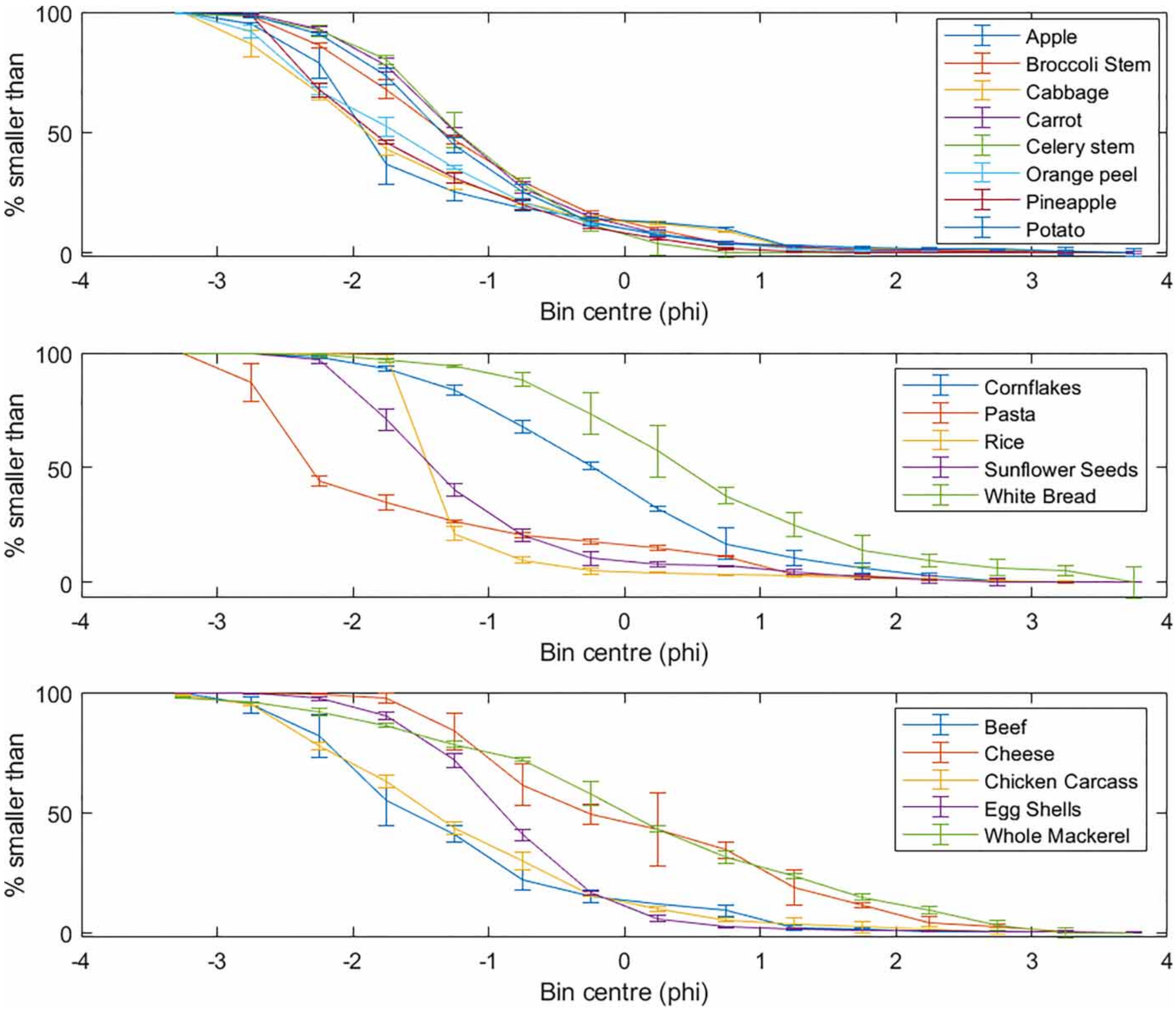

Figure 3 | Cumulative size distribution for 18 food types: (top) vegetables & fruit; (middle) bakery & staples; (3) meat/fish & dairy/eggs. Error bars represent standard deviation of repeated measurements.

Some analytical distribution types are known to be used to characterise particle size distributions in soils and other granular materials. This enables empirically derived distributions to be approximated by a simple analytical expression with a small number of parameters. A common distribution function for particle size distributions is the Gamma distribution (Equation (9)):

$$f(x) = \frac{(x/b)^{a-1}\exp(-x/b)}{b\Gamma(a)} \tag{9}$$

where x is the positive particle size, a is the shape parameter (producing a unimodal skewed distribution for $a > 1$, with less skew as a increases), b is the scale factor (which has the effect of stretching or compressing the range of the distribution), and Γ is the Gamma function.

For each food type, a Gamma distribution was fitted to the particle size distribution data using a least-mean-squares optimisation method. The optimised values of a and b are presented in Table 4, along with the root-mean-square error in units of percentage points. The data are presented in order of fit quality (best to worst).

The a parameter is always above 1, meaning a 'humped' distribution shape, and varying generally between 2 and 13 as distributions are more or less skewed. Rice is a clear outlier with $a = 39.21$ as the distribution is a very clear and symmetrical peak (see Figure 2). The b parameter generally varies between 0.3 and 1.5 as the distributions are broader or narrower, again with rice as an outlier at $b = 0.06$ as

Table 3 | Mean particle size and standard deviation for the 18 characterised food types, ordered by mean particle size

Food type	Mean particle size (phi)	Standard deviation (phi)	Mode (phi)	Mean particle size (mm)	Standard deviation (mm)	Mode (mm)
Pasta	−1.43	1.38	−2.25	2.70	0.39	4.76
Pineapple	−1.34	0.95	−2.25	2.53	0.52	4.76
Cabbage	−1.31	1.25	−1.75	2.48	0.42	3.36
Orange peel	−1.28	1.09	−2.25	2.42	0.47	4.76
Apple	−1.26	1.22	−1.75	2.39	0.43	3.36
Beef	−1.08	1.13	−1.75	2.11	0.46	3.36
Chicken carcass	−1.02	1.16	−1.25	2.03	0.45	2.38
Rice	−1.01	0.70	−1.25	2.01	0.62	2.38
Broccoli stem	−0.94	1.01	−1.25	1.92	0.50	2.38
Sunflower seeds	−0.94	0.96	−1.25	1.92	0.51	2.38
Cheese	−0.93	0.76	−1.25	1.90	0.59	2.38
Potato	−0.92	1.02	−1.25	1.89	0.49	2.38
Carrot	−0.85	0.94	−1.25	1.80	0.52	2.38
Egg shell	−0.61	0.77	−0.75	1.53	0.59	1.68
Cornflakes	0.06	1.11	0.25	0.96	0.46	0.84
Whole mackerel	0.27	1.54	0.25	0.83	0.34	0.84
Celery	0.28	1.27	−0.75	0.82	0.41	1.68
White bread	0.78	1.25	0.75	0.58	0.42	0.59

Table 4 | Gamma distribution parameters and root-mean-square error of optimised Gamma distributions, ordered by best fit

Food type	a	b	RMS error (% points)
Rice	39.21	0.06	1.93
Egg shell	6.13	0.33	0.93
Apple	10.14	0.39	4.45
White bread	2.92	0.39	1.64
Sunflower seeds	6.77	0.44	1.90
Pasta	12.20	0.44	5.47
Celery	5.07	0.52	1.51
Carrot	4.90	0.57	1.11
Cornflakes	2.99	0.60	1.21
Potato	4.86	0.62	1.16
Pineapple	4.69	0.98	4.11
Broccoli stem	3.46	1.01	0.83
Cheese	2.28	1.01	3.94
Beef	3.76	1.08	3.10
Whole mackerel	1.87	1.21	1.96
Cabbage	3.87	1.33	2.61
Chicken carcass	3.00	1.39	1.94
Orange peel	3.27	1.49	2.76

the distribution is very narrow. There appears to be no clear pattern of certain food groups exhibiting certain distribution parameters.

It can be seen that the majority of foods have a root-mean-square error below three percentage points, indicating that the Gamma distribution fits very well. The worst fits were obtained for pasta, apple and pineapple. This is likely due to the partially irregular and/or bimodal nature of their size distributions (see Figure 2). The psd and fitted Gamma curves for these three foods are shown in Figure 4 along with the best case fit (broccoli stem) for reference. The highest error of 5.47 percentage points for pasta is still a reasonably good fit and characterises the general shape of the distribution as shown in the figure.

Maximum settling velocity

Figure 5 shows the settling velocity of each food type as a function of each particle size fraction, while Figure 6 shows the cumulative mass percentage by maximum settling velocity. The maximum settling velocities for all food types, except egg shell, were below 0.1 m/s. Fruits, vegetables, meat/fish, pasta, and cheese were all well below 0.1 m/s, with grains such as rice and pasta showing slightly higher maximum

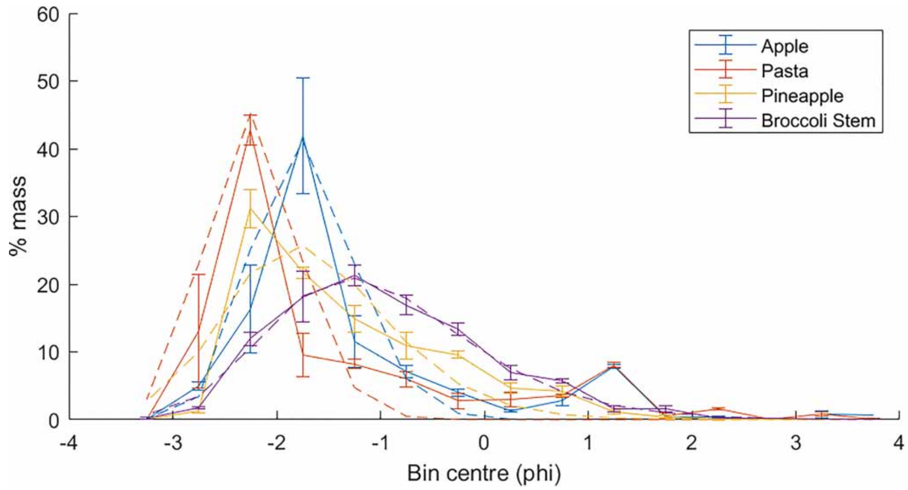

Figure 4 | Gamma distribution fitted to four food types showing the best (broccoli stem) and worst (pasta, pineapple, apple) fitting cases. Solid lines are measured data. Error bars are standard deviation of repeated measurements. Dashed lines are fitted Gamma distributions.

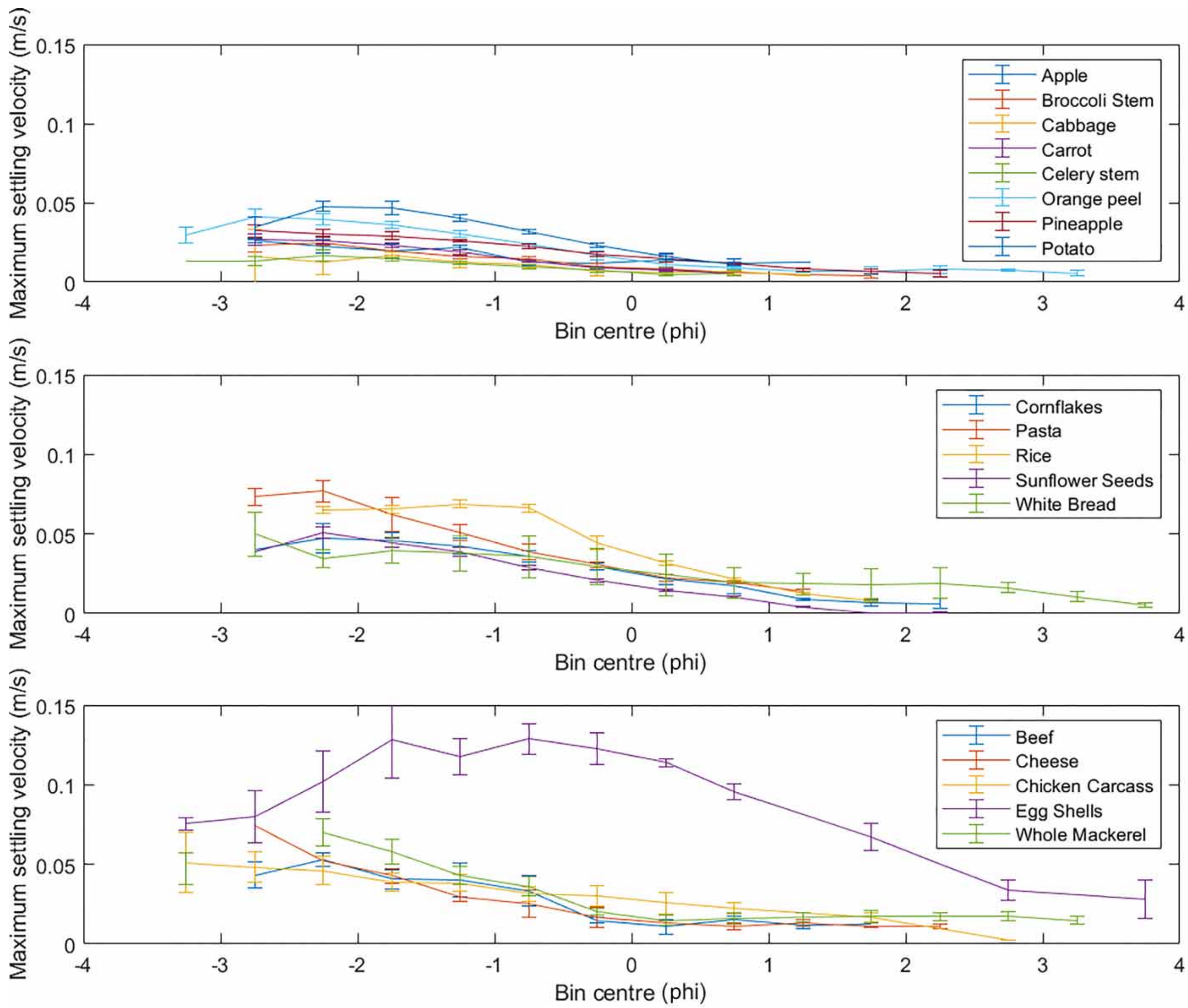

Figure 5 | Maximum settling velocity by particle size for all food types, (a) fruits and vegetables, (b) staples and grains, (c) meats, fish and dairy.

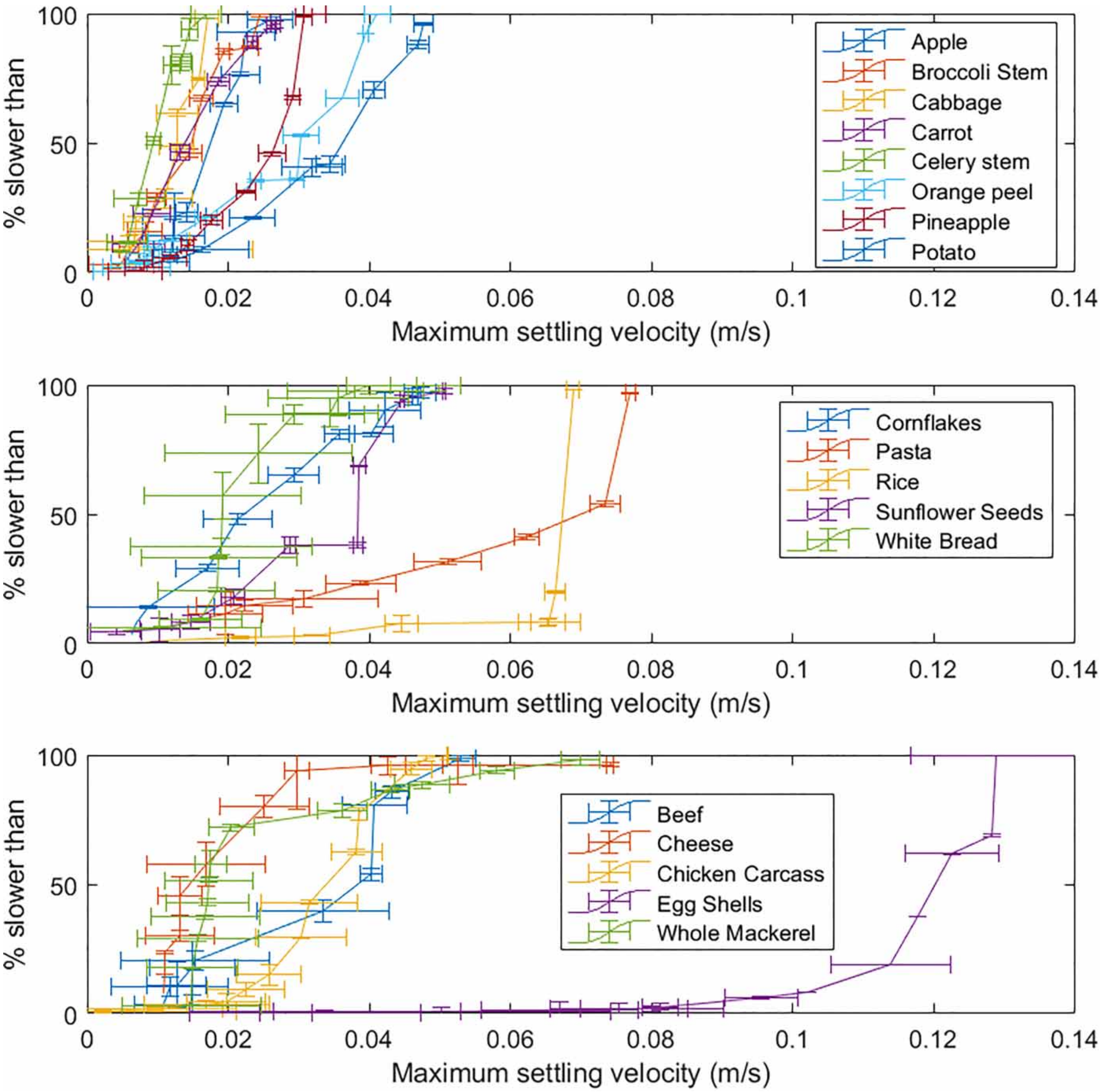

Figure 6 | Cumulative mass percentage by maximum settling velocity.

particle settling velocities. The clear outlier was egg shell which showed maximum settling velocities over 0.1 m/s for many particle sizes and for the largest particle sizes up to almost 0.13 m/s. For some foods the maximum settling velocity of particles within some sieve sizes could not be measured as the number of particles collected from this fraction was too low to enable measurement. The standard deviation between repeated measurements of particle fall velocity was calculated for size fractions of each food type. Averaged across all sizes and foods, the standard deviation of the particle fall velocity was around 4 mm/s within a size fraction. Generally the standard deviation of the maximum particle fall velocity within a size fraction averaged across each food type was below 5 mm/s, except for chicken carcass (7 mm/s), white bread (9 mm/s) and egg shell (11 mm/s). This is likely due to the complex nature of chicken carcass (mixture of bone, sinew, flesh etc.), variability of white bread size fractions (see Figure 3) and the larger measurement uncertainty for egg shells, possibly due to the particle shape and also as the fall velocity was much higher than for other foods.

Figure 6 illustrates that egg shells, ground pasta and rice are likely to provide the food particles with the highest likelihood of deposition. It can be seen for all three food types that the majority of the ground food has high maximum settling velocities. This indicates that rice, pasta and especially egg shells, are the food types that need to be examined for the risk of deposition in downstream sewers.

Particle transport potential

The data of particle density, calculated according to the 'Particle entrainment' section, indicated that for all the studied food types except egg shells, the particle densities ranged from 1,006 kg/m^3 to 1,059 kg/m^3 (see Table 5). Only the egg shells indicated a higher density of around 1,165 kg/m^3. Using the d_{95} values and the particle density values it was possible to estimate a boundary shear stress (τ_{crit}) that would entrain the maximum particle sizes for each food group using the widely used Shields criterion – Equation (6). As can be seen in Table 6 these boundary shear stresses (estimated using a conservative value of Shields Number of 0.065) ranged from 0.01 to 0.15 N/m^2, values that would be commonly encountered in many foul and combined sewers during dry weather flow. Only the egg shells with an apparent particle solid density of 1,165 kg/m^3 required a boundary shear stress of 0.38 N/m^2, a significantly higher value. It was decided to examine the entrainment behaviour of egg shells in more detail for two reasons: (i) it is the food group that has a significantly higher shear stress threshold than all the other food groups; (ii) visual inspection indicated that the egg shell particles were not spherical in shape and so weaken the assumptions used in Equations (4) and (5).

Erosion meter tests were conducted for egg shell particles as described in the 'Particle entrainment' section. The shear stress observed to entrain deposited egg shell particles is shown in Figure 7 and is higher than estimated and reported in Table 6. Error bars on the data indicate the maximum and minimum shear stress measured for repeated tests. While the apparent density of egg shell based in its settling velocity was 1,165 kg/m, direct measurements of egg shell density by Carter (1968) indicate that the density of egg shell is 2,241 kg/m^3 ± 4 kg/m^3. If this value is used with the estimated shear stress from the erosion meter tests, it can be seen that the Shields number (Equation (6)) is close to 0.065 on average (threshold for sustained particle movement), varying non-linearly from 0.036 to 0.078 depending on particle size, and suggesting that the shape of the egg shell particles at the different size fractions may also have an effect on their entrainment. Larger egg shell particles are observed to have a plate-like shape with lower sphericity. This leads to a larger deviation from

Table 5 | Apparent particle density for the largest practical particle sizes of FWD-derived particles for 18 food groups

	Apple	Beef	Broccoli stem	Cabbage	Carrot	Cheese	Celery stem	Chicken carcass	Cornflakes	Egg shells	Orange peel	Pasta	Pineapple	Potato	Rice	Sunflower seeds	White bread	Whole mackerel
d_{95} (mm)	5.69	5.79	5.17	7.11	4.68	2.64	4.74	5.65	3.26	3.59	6.59	7.10	4.48	4.86	2.79	3.91	2.28	7.88
V_{95} (m/s)	0.026	0.043	0.024	0.017	0.026	0.040	0.016	0.048	0.047	0.111	0.037	0.073	0.031	0.041	0.043	0.050	0.039	0.050
ρ_s (kg/m^3)	1,006	1,015	1,006	1,002	1,009	1,049	1,005	1,022	1,046	1,165	1,011	1,033	1,015	1,021	1,051	1,040	1,059	1,015

Table 6 | Estimated entrainment threshold shear stress value for 18 common food groups

	Apple	Beef	Broccoli stem	Cabbage	Carrot	Cheese	Celery stem	Chicken carcass	Cornflakes	Egg shells	Orange peel	Pasta	Pineapple	Potato	Rice	Sunflower seeds	White bread	Whole mackerel
τ_{crit} (N/m^2)	0.02	0.06	0.02	0.01	0.03	0.08	0.02	0.08	0.10	0.38	0.05	0.15	0.05	0.07	0.09	0.10	0.09	0.08

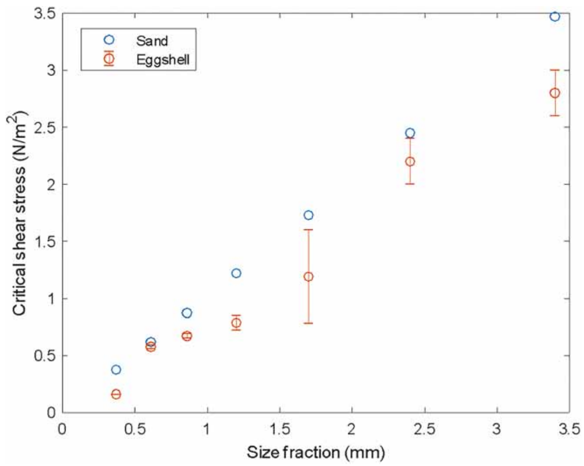

Figure 7 | Egg shell mobility.

spherical behaviour for the larger particles. Error bars are also larger for larger particle sizes due to the plate-like behaviour and the larger size intervals. It should also be noted that at all size fractions the shear stress required to mobilise egg shell particles was lower than the shear stress required to move equivalent sized sand particles.

DISCUSSION

The tests reported here are intended to contribute to the better understanding of the nature and potential behaviour of FWD derived particles and the implications of their input into sewer systems. The careful testing and clearly defined and followed protocols for examining individual food types provide scientific robustness and confidence that the results are both repeatable and realistic.

Careful laboratory testing has provided detailed descriptions of particle size distributions (psd) at ½ phi intervals for ground food waste from a single FWD model for 18 food types that are commonly found in the UK. These psd descriptions have a single mode, with a range of modal sizes and widths of the distributions. The shape of the particle size distributions is repeatable for particular food types but there are no clear similarities among food types within a given food group. The distributions were described well by Gamma distributions, which agrees with other studies of granular and ground materials.

Samples from the individual size fractions were collected and the maximum fall velocity was determined for each particle size fraction. This work has demonstrated that the highest fall velocities were found for pasta, rice and egg shell. The shape of the mass distributions for these food types showed that significant amounts of each had fall velocities above 0.06 m/s.

The values of maximum fall velocity did not link directly with particle size for different food types, indicating a variation in particle density. Taking the maximum practical size fraction (d_{95}), its fall velocity and assuming the particles were spherical, it was seen that there was a variation in particle density, and that for 17 out of the 18 food types these values were close to the density of water. One food type, egg shells, indicated a higher density and this food type was subjected to further investigation.

The detailed particle size distributions measured in this study correspond with the limited particle data obtained in earlier studies (Galil & Shpiner 2001; Kegebein *et al.* 2001; Channon *et al.* 2013; Drinkwater *et al.* 2015), although the data from these studies were generally of very low resolution so an objective comparison is difficult. The study by Drinkwater and colleagues using cooked food appears to be an outlier with this and other studies with regard to the particle size distribution of ground food waste, generally showing larger particle sizes.

Analysis using the maximum practical size fraction (d_{95}) for all the food groups indicated that the boundary shear stress needed to entrain FWD particles was low in comparison to boundary shear stresses found in most foul and combined sewer pipes. For egg shells further tests indicated that the boundary shear stress required to entrain these particles is considerably higher than for FWD-derived particles of other food types, most likely due to the higher density and is likely to be also affected by lower particle sphericity. It is clear that particle density is the most important particle parameter in determining the entrainment threshold for FWD particles. While the likelihood of egg shell settling is higher than other food types, egg shell deposits can be assumed to be moved by normal peak dry weather flows, and nonetheless egg shells only comprise around 1% of the overall mass of food waste so the likelihood of creating significant in-sewer deposition in sewer networks is very low.

CONCLUSIONS

It has been shown that for 18 common food types the modal particle size varied between 0.59 mm and 4.76 mm and the standard deviation varied between 0.34 mm to 0.62 mm. Particle size distributions are shown to conform well to Gamma distributions, meaning they can be characterised by just two parameters.

Particle densities were estimated using particle size and fall velocity data. This analysis demonstrated that most FWD particles had particle densities close to that of water. This results in these particles being entrained into motion at low values of boundary shear stress. The ease of entrainment means that the vast majority of food types is highly unlikely to form persistent deposits in sewer pipes.

Egg shell particles showed a submerged density estimate considerably higher than the other food types, and thus the entrainment threshold was considerably higher than for the other food types. The deposition risk of egg shells is thus higher than for other food types, however its overall prevalence in waste food is very low (around 1%) so it is unlikely to cause significant practical deposition issues.

These studies have shown that, by employing the robust experimental method described, the deposition risk of FWD derived particles can be assessed. Further work should expand the range of food types, and explore the implications when applied to flows in a range of sewer systems.

ACKNOWLEDGEMENTS

Stream CDT (EP/L015412/1) & InSinkErator UK Ltd – PhD funding Leo Russell Moore – Egg shell mobility measurements.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. Available online: https://doi.org/10.5281/zenodo.3697302.

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First received 2 February 2021; accepted in revised form 9 April 2021. Available online 3 May 2021