

# Characterising faecal particle settling hydrodynamics to reenvision solid-liquid separation in decentralised sanitation systems

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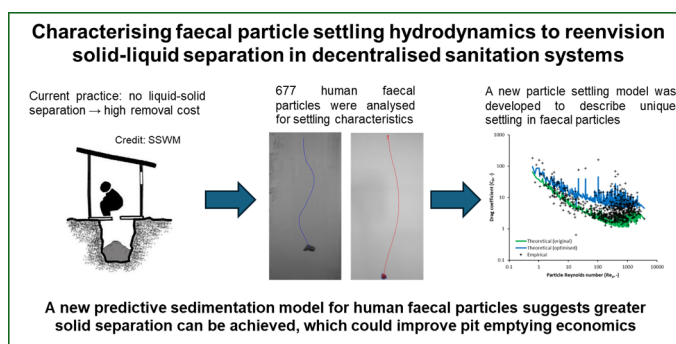
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## HIGHLIGHTS

- A dataset of 677 human faecal particles was analysed for settling characteristics.
- Particles above 3 mm in size were found to deviate from existing settling models.
- A revised settling model was developed to better describe faecal settling.
- The revised model suggests faecal settling can be enhanced to improve pit emptying.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

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## ABSTRACT

Given the scarcity of empirical data, current literature employs the Bristol Stool Scale (BSS) as a surrogate for evaluating the role of faecal structural characteristics in solid-liquid separation efficiency. To establish a more definitive relationship, this study quantified the settling velocity of 677 individual fresh faecal particles, enabling explicit correlations between particle drag and physical attributes (size and shape), and implicit associations with morphological features via BSS classification. For faecal particles below 3000  $\mu\text{m}$ , settling velocity could be relatively well described by existing models that assume viscous forces dominate drag. However, the particle population largely exceeded this threshold size, where the role of particle aspect ratio and inertial forces were evidenced to be of primary importance to solid-liquid separation. Modelling of particle drag was undertaken to account for particle shape irregularity and particle rotation across the particle size range but led to an over-estimation of settling velocity due to its derivation being based on the hydrodynamic behaviour of solid particles. The deviation was accounted for by the diversity in fractal character amongst the particle population, which can enhance drag; a contribution which can be inferred from morphological classification provided by the BSS. The constants associated with the irregular solid particle model were therefore interrogated to improve estimation of particle settling for fresh faeces across the three flow regimes (namely Stokes, intermediate and turbulent). Current sanitation practice does not take advantage of solid-liquid separation in existing pit latrine design. The

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revised particle model permits solid-liquid separation design for fresh faecal sludge, where the volume reduction provided by fast effective segregation of high solids concentration particles can transform sludge transportation costs, which remains the critical economic barrier to achieving safe and affordable sanitation.

## 1. Introduction

Over 3.1 billion people currently require access to onsite non-sewered sanitation (Cheng et al., 2022). Poorly constructed containment within pit latrines, and the illegal discharge of pit latrine sludge increases the incidence of contamination within local surface water and groundwater resources. This poses risk of environmental harm and increases the exposure of people to faecal pathogens (Saxena and Den, 2022; Thye et al., 2011), resulting in 700,000 child deaths each year (BandMGF, 2016). The cost of pit latrine emptying can exceed 50 % of a household's monthly income in low-income areas, creating a substantive economic barrier to the use of formal sanitation services (Peletz et al., 2020). Faecal particles (or faeces) are subject to high levels of shear stresses in current pit latrine design from exposure to the steep drop between the user and the collection chamber which causes fragmentation, and alteration of the morphology and particle size distribution (Ramesh et al., 2006; Sam et al., 2022; Ward et al., 2023). This shear-induced fragmentation disrupts the networked particle structure, lowering the gel point of the suspension. The gel point represents the solids concentration at which the faecal matrix exhibits a yield stress (Mercer et al., 2021a). Consequently, pit latrine sludge is shown to exhibit a higher yield stress than fresh faecal particles due to this shear history (Mercer et al., 2021b) which results in a matrix that is more difficult to pump. Emptying costs are largely determined by the additional water that must be added to reduce the apparent viscosity of faecal sludge to improve pumpability (Gold et al., 2016; Septien et al., 2018). Water addition restricts the number of pit latrines that can be serviced each day, as the sludge volume increases by more than five times and in dense urban settings tankers are restricted in volume (up to 1000 kg) (Mikhael et al., 2014). This is the primary barrier hindering the economic feasibility of safe pit latrine emptying and is why <0.3 % of pit latrine faecal sludge reaches treatment sites in some low-income countries (Ross et al., 2016). Improving the economic viability of faecal sludge management is therefore of critical importance to achieving access to safe sanitation for all (Sustainable Development Goal 6).

Solid-liquid separation is not currently incorporated into standard pit latrine design. The total solids concentration of pit latrine sludge before dilution (to aid pumping) is reported to be around 6 %wt, dependent upon latrine construction (Wanda et al., 2021), which exceeds the solids underflow of a municipal sewage primary clarifier (~3 %wt.). By contrast, fresh faeces comprise total solids concentrations of between 14 and 37 %wt. (Rose et al., 2015). The fresh faeces volume is therefore over an order of magnitude less than pit latrine sludge, for an equivalent mass of total solids. Fresh faeces also offer improved flowability and dewatering characteristics when compared to pit latrine sludge (Mercer et al., 2021a, 2021b). Consequently, incorporation of solid-liquid separation into pit latrine design to segregate the fresh faeces solids fraction from the liquid fraction could transform the economics of pit latrine emptying by producing a smaller volume of material with improved pumping characteristics, that is faster and easier to dewater once transported to a centralised facility.

Solid-liquid separation within gravity settlers or thickeners is determined by fixing the retention time within the settling zone based on the assumption that particle movement is unhindered (*Type I settling*). At low Reynolds numbers (laminar region), particle movement is dominated by viscous forces, and the drag coefficient is larger since momentum is transferred further into the fluid (Bagheri and Bonadonna, 2016). Particle settling within the laminar region is described by Stokes' law which is generally adequate for the characterisation of particle settling within primary clarifiers at centralised wastewater treatment

works, due to the relatively small particle size of raw municipal sewage ranging from 27–150  $\mu\text{m}$  (Houghton and Stephenson, 2002; Ward et al., 2021, 2023). However, fresh human faeces have not been exposed to the shear forces asserted during sewer transmission, and therefore commonly exceed 10,000  $\mu\text{m}$  in length (Penn et al., 2018b). For this size range, particle motion becomes dominated by transitional and turbulent flows, where the inertial forces resulting from the displaced fluid begin to influence the drag force acting on the particle (Ireland et al., 2016; Loth, 2008). Cliff and Gauvin (1971) proposed a correlation to collectively describe the drag coefficient acting on particles across all three flow regimes. However, this was based on solid spheres, which do not reflect the physical form of human faeces where the shape and aspect ratio are recognised to be increasingly heterogeneous with particle size. Bagheri and Bonadonna (2016) proposed an alternate method to characterise the drag coefficient to reflect heterogeneity in particle shape and aspect ratio across all three flow regimes. The resultant method provided a low residual error, but similar to previous research (Cliff and Gauvin, 1971), only solid shapes were considered with this approach. Human faeces can comprise of fractal morphology, which will reduce the settling velocity versus that estimated using a hard sphere model (Crittenden et al., 2012). Shape, orientation and consistency may also uniquely contribute to the settling behaviour of human faeces which cannot presently be accounted for within existing models of particle drag. This study therefore provides the first experimental characterisation of the settling behaviour of fresh human faeces to advance the design of solid-liquid separation within decentralised sanitation systems. To facilitate this characterisation, the settling behaviour of 677 fresh faecal particles was experimentally measured to relate particle form to particle flow characteristics. In the health literature, distinctions in physical form are generally characterised with reference to the Bristol Stool Scale (BSS), which has more recently been adopted within sanitation literature as a proxy indicator for how structural composition of these difficult to analyse particles can inform solid-liquid separation (Penn et al., 2018a). Faecal particles are therefore sorted by BSS to ascertain the relevancy of this classification to particle hydrodynamics across the three discrete flow regimes. The role of particle shape and wider intrinsic morphological differences on particle motion are subsequently investigated and compared to existing models for the estimation of drag coefficient based on 'hard sphere' and 'irregular' shapes to determine their validity for the description of fresh human faeces particle hydrodynamics. Finally, due to the challenge with measuring discrete particle characteristics in human faeces that may contribute towards drag, this study interrogates the constants contained within models describing particle settling within each flow regime, through fitting the empirical data collected. The intended outcome is to provide a model that can collectively describe settling for non-solid particles of heterogeneous shape and aspect ratio across all three flow regimes, that can serve as a basis for solid-liquid separation design within a non-sewered sanitation context.

## 2. Materials and methods

### 2.1. Experimental setup and image analysis

Settling velocity was characterised using methods adapted from literature (Wang et al., 2018). A rectangular settling column of 0.15 m width was used to determine drag coefficient for particles primarily within the Stokes and intermediate regime ( $Re_p < 1000$ ), corresponding to particle sizes below 0.03 m. Due to the particle size range, it was necessary to modify the experimental setup to extend the field of view

| Bristol Stool scale | Morphology                                                                        | Description                                         | Health implication                                                         |
|---------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------|----------------------------------------------------------------------------|
| Type 1              |  | Hard dense lumps                                    | Indicative of constipation, bloating and stomach pain                      |
| Type 2              |  | Sausage shaped and lumpy                            |                                                                            |
| Type 3              |  | Sausage shaped but with fractured (cracked) surface | Easy to pass, indicating a healthy stool                                   |
| Type 4              |  | Sausage shaped but smooth                           | Easy to pass, indicating a healthy stool                                   |
| Type 5              |  | Soft discriminate pieces with defined edges         | Indicating lack of fibre, with structure reflecting beginning of diarrhoea |
| Type 6              |  | Mushy stool                                         | Indicating diarrhoea                                                       |
| Type 7              |  | Watery stool                                        | Very loose structure, indicating diarrhoea                                 |

**Fig. 1.** Qualitative description of the Bristol Stool Scale which was introduced for the diagnostics of human health (Heaton et al., 1992) through classification of faeces based on shape and form.

for larger particles. Therefore, a 1.5 m high cylindrical column (internal diameter 0.26 m) was constructed for particles greater than 0.03 m ( $Re_p$  1000 – 4000). In each experiment, a single particle was released into the centre of the settling column with zero initial velocity, with images captured to determine velocity toward the base of the column. Wall effects on the particle settling velocity were assumed to be negligible, due to the difference between column and particle diameter, the location of the measurement window in the middle of the columns, and the rejection of any results for samples that moved away from the column centreline by more than half the distance to the column wall (Clift et al., 1978; Happel and Brenner, 1983). The temperature of the settling fluid (tap water) was consistently maintained at  $19 \pm 1$  °C. A standard working distance (from lens to where particle was released) was used for each setup, and a graticule introduced within the field of view to calibrate sizing. Digital cameras were used to capture particle settling, at 15 fps in the small column (Sony ICX674) and 25 fps in the large column (a Canon digital SLR). The fields of view of the respective cameras were 0.50 m x 0.28 m for the large column and 0.3 m x 0.075 m for the small column, and based on previously reported methods (Wang et al., 2020). Depending on the particle velocity and the field of view of the camera, between 9 and 654 frames of falling particles were captured in each run. The measurement uncertainty was estimated based on the product of the exposure time to the maximum particle velocity measured (Bagheri and Bonadonna, 2016), which resulted in a particle position uncertainty range between  $0.33 \mu\text{m}$  -  $5.88 \mu\text{m}$  and  $0.10 \mu\text{m}$  -  $7.63 \mu\text{m}$  for the large and small columns respectively, corresponding to a measured velocity error of  $<0.002$  % and  $<0.008$  %. Particle velocities were estimated through frame-by-frame and multi-frame particle tracking using imaging software (ImagePro Premier v9.1, Media Cybernetics Inc, Maryland, USA). The particle velocity was estimated along the vertical axis (y-plane) between specific bounds ( $v_y$ ). Within this region, the terminal settling velocity can be verified by determining that the particle has achieved a near-constant velocity across several consecutive measured distances (Fig. 2). The linear particle settling velocity (in the vertical y-plane,  $v_y$ ) was characterised for each particle across six distinct Bristol Stool Scale (BSS) classes and related to the particle mean calliper. Larger particles are more likely to experience wake instability and oscillations due to the differential forces and momentum acting on each particle (Ern et al., 2012). Consequently, a second measurement was introduced to

infer the extent to which particle size, shape and aspect ratio of human faeces may alter settling velocity when subjected to distinct flow regimes (actual particle velocity,  $v_a$ ). This was estimated by tracking the centroid of each particle in the ImagePro software, and calculating the absolute distance travelled per frame, divided by the frame exposure. Whilst  $v_a$  provides insight into a particle's lateral movement during settling,  $v_y$  describes its direct settlement in the vertical direction, and therefore has been used for the calculation of drag coefficients in this study. Size and aspect ratio of each particle was analysed using the mean, minimum and maximum calliper, area and circularity incorporated as simple shape descriptors, which were all calculated directly by the ImagePro software with Feret diameters being used for the calliper measurements. The size and shape descriptors for each particle were based on physical measurements from images taken at each video frame, which provided for imaging of particles across multiple orientations to achieve an averaged value that can represent their heterogeneity (Eq. (1)):

$$C = \frac{4\pi A}{P^2} \quad (1)$$

where, C is circularity, A is area ( $\text{m}^2$ ) and P is perimeter (m). For consistency, faeces that did not settle ('floaters') were also subject to image analysis to determine particle size, and a settling velocity of  $0 \text{ m s}^{-1}$  recorded. Hence, particle settling velocities set to  $0 \text{ m s}^{-1}$ , represent the proportion of the total particle population that do not settle. Floating particles were added to the settling columns and left for a minimum of 10 s to ensure settlement did not incur, before being captured by a still-frame photograph on the Canon Digital SLR for image analysis.

## 2.2. Faecal material collection and qualitative description

Human faecal samples were collected anonymously from 14 volunteers, using a protocol approved by the Cranfield University Research and Ethics System (CURES 3022). Volunteers were Cranfield University staff members, between the ages of 18 and 65, who self-declared as being fit and healthy. No information on gender, diet, or medical history was collected. The faecal sludge samples were collected independently and were therefore free of urine contamination. Collected samples were tested within 24 h of collection. If stored for more than four hours, they were refrigerated at 4 °C and allowed to equilibrate to room temperature

before testing. Collected faecal samples ranged from type 1 to type 6 on the Bristol Stool Chart (Fig. 1). Type 1 is characterised by separated hard lumps, indicative of constipation, while Type 6 is visually soft, liquid and mushy, more closely relating to a diarrhoeal event. A total of 49 faecal samples were obtained across this range and subsampled into 677 particle specimens with maximum calliper measurements ranging 360  $\mu\text{m}$  to 76,380  $\mu\text{m}$ . Of the 49 samples collected, 2<sup>no.</sup> (4 %) were classified as BSS1, 4<sup>no.</sup> (8 %) BSS2, 8<sup>no.</sup> (16 %) BSS3, 17<sup>no.</sup> (35 %) BSS4, 7<sup>no.</sup> (14 %) BSS5, and 11<sup>no.</sup> (22 %) as BSS6. Due to the challenging matrix composition, the direct determination of faecal sludge density was not possible. A literature value for faecal sludge density of 1170  $\text{kg m}^{-3}$  was assumed (Penn et al., 2018).

### 2.3. Settling theory

Particle settling can be discretised into three flow regimes, dependent on the particle Reynolds number ( $Re_p$ ) which is a dimensionless quantity that characterises the ratio of inertial to viscous forces acting on a particle as it settles in a fluid. Stokes regime describes conditions where settling is characterised by  $Re_p$  considerably below 1, which is consistent with primary sedimentation tanks used for solid-liquid separation of untreated sewage in centralised wastewater treatment works, where particle sizes are ordinarily <100  $\mu\text{m}$  in diameter (Houghton and Stephenson, 2002; Ward et al., 2021, 2023). Within this regime, inertial forces are minimal, and particle settling becomes dominated by viscous forces. This is illustrated through Stokes' analytical solution, in which inertial terms are negated, so the drag coefficient ( $C_D$ ) on a smooth spherical particle can be described as (Eq. (2)):

$$C_D = \frac{24}{Re_p} \quad (2)$$

This solution has been shown to provide reasonable description of spherical particle settling within this domain (Roostae et al., 2022). From  $Re_p$  0.1 to 1000, flow separation begins, starting with wakes forming behind spherical particles, which become less stable as  $Re_p$  is increased. Like Stokes' regime, the drag coefficient declines within this Intermediate regime, but the extent of change reduces as  $Re_p$  is increased. Once spherical particles are exposed to Newton's regime ( $Re_p > 1000$ ), the succeeding wakes are fully turbulent. At this point, the drag coefficient of a sphere tends toward a constant value. Clift and Gauvin (1971) provided a generalised analytical solution to collectively describe the drag coefficient for spherical particles across all three flow regimes (Eq. (3)):

$$C_D = \frac{24}{Re_p} (1 + Re_p^{0.687}) + \frac{0.42}{1 + \frac{42500}{Re_p^{1.16}}} \quad (3)$$

The empirical constants provide an indication of the relative contribution of the discrete forces acting on the particle population within the prescribed regime. However, the drag coefficient also exhibits a first-order dependency upon shape and orientation, which can introduce secondary motions of particles (Bagheri and Bonadonna, 2016). Consequently, the drag coefficient must be adjusted to compensate for non-uniform particle populations. Faecal particles are characterised by a broad size distribution, from several hundred micrometres to cm in scale (Mercer et al., 2021a). Due to the shear and compression history of human faecal sludge, the shape and orientation of faecal particles can also be expected to change for larger  $Re_p$  which must be accounted for. To incorporate the role of non-uniformity, shape factors for non-spherical particles termed Stokes' ( $k_s$ ) (Eq. (4)) and Newton's ( $k_N$ ) (Eq. (5)) drag corrections were introduced (Ganser, 1993):

$$k_s = \frac{C_D}{C_{D,s}} = \frac{C_D}{\left(\frac{24}{Re_p}\right)} \quad (4)$$

$$k_N = \frac{C_D}{C_{D,s}} = \frac{C_D}{0.463} \quad (5)$$

where  $C_{D,s}$  is the drag coefficient of a sphere with same volume and  $Re_p$  as the particle. While correlations exist to estimate  $k_s$  and  $k_N$ , they are generally limited to describing more uniform particle populations, where the implications of non-isometric shapes or the settling of non-spherical particles in a specific orientation were not accounted for in the drag coefficient. Subsequently, an estimation of drag coefficient was developed that could collectively describe both regular and irregular particles moving in fluids, while also considering the effects of secondary particle motion and orientation (Bagheri and Bonadonna, 2016) (Eq. (6)):

$$C_D = \frac{24k_s}{Re_p} \left( 1 + 0.125 \left( \frac{Re_p k_N}{k_s} \right)^{23} \right) + \frac{0.46k_N}{1 + \frac{5330}{\left( \frac{Re_p k_N}{k_s} \right)}} \quad (6)$$

In the Bagheri and Bonadonna equation, the Stoke's drag correction (Eq. (7)) and Newton's correction (Eq. (9)) were also refined:

$$k_s = \frac{(F_s^{1.3} + F_s^{-1.3})}{2} \quad (7)$$

where (Eq (8)):

$$F_s = fe^{1.3} \left( \frac{d_{eq}^3}{LIS} \right) \quad (8)$$

$$k_N = 10^{\alpha_2 [-\log(F_N)]^{\beta_2}} \quad (9)$$

where (Eqs. (10)-(12))

$$F_N = f^2 e \left( \frac{d_{eq}^3}{LIS} \right) \quad (10)$$

$$\alpha_2 = 0.45 + \frac{10}{\exp(2.5 \log \rho' + 30)} \quad (11)$$

$$\beta_2 = 1 - \frac{37}{\exp(3 \log \rho' + 100)} \quad (12)$$

where,  $\rho'$  is the particle to fluid density ratio ( $\rho_p/\rho_f$ ). The form factors ( $F_s$  and  $F_N$ ) facilitate accuracy of the Bagheri and Bonadonna model over a wide range of non-spherical particles due to their incorporation of shape considerations such as flatness (f), elongation (e), and longest (L), intermediate (I), and shortest (S) particle length.

This expression was shown to be experimentally valid across a range of solid non-spherical geometries. In this study we explore its validity to describe solid-liquid separation for faecal sludge, which is a distinctive heterogeneous and compressible particle population comprising a broad range of particle size, shape, orientation, roughness and fractal dimension. Subsequent fitting of this expression to the experimental data collected in this study, was undertaken using a non-linear regression Solver (Frontline Systems, Nevada, USA) within Excel (Microsoft Corp., Seattle, USA) following the method of Billo (2007).

## 3. Results and discussion

### 3.1. Relating particle settling velocity to Bristol stool scale

Particle velocity increased reasonably consistently with an increase in mean calliper for the particle population below a threshold of around 3000  $\mu\text{m}$  (vertical line, Fig. 3). However, beyond this threshold, the variance in linear particle velocity increased with larger particle sizes, which is consistent with previous observations for other particle

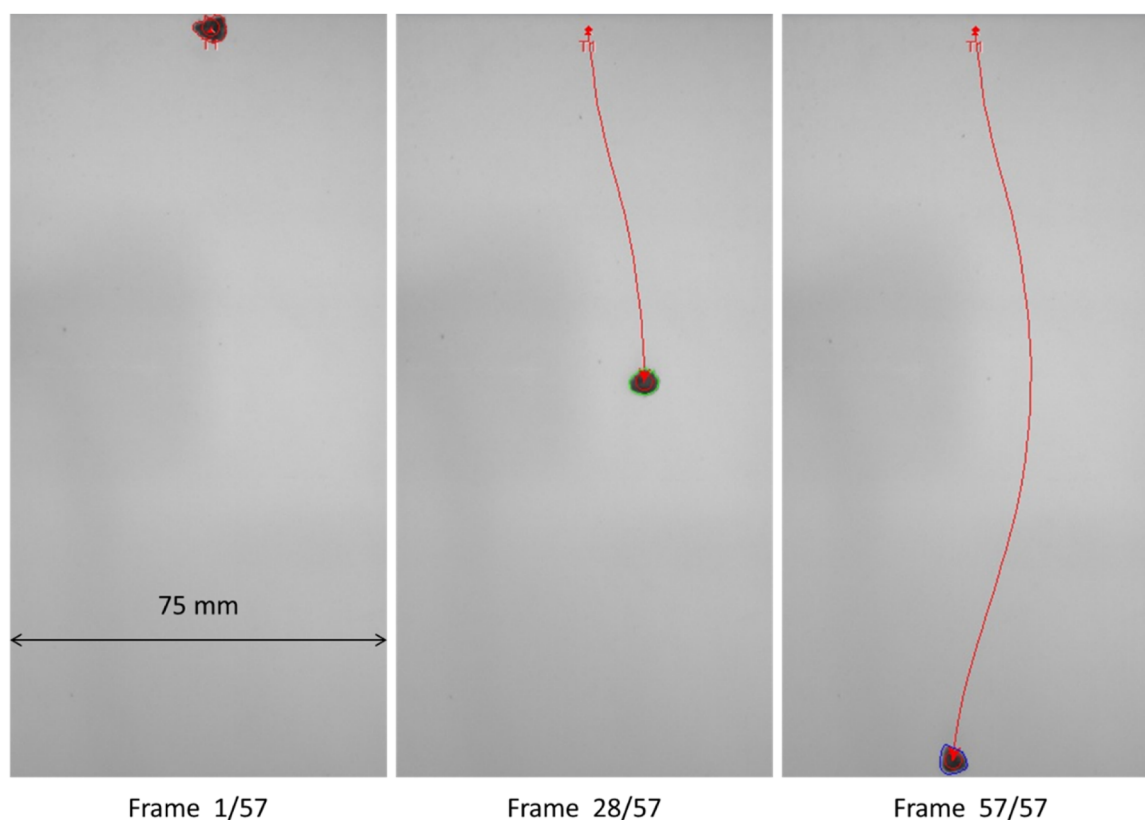


**Fig. 2.** Digital imaging used for particle tracking of individual fresh human faecal particles, illustrated in the small column at an image capture rate of 15 frames per second. Data analysis for particle tracking was performed using imaging software (ImagePro Premier, v9.1, Media Cybernetics Inc., Maryland, USA).

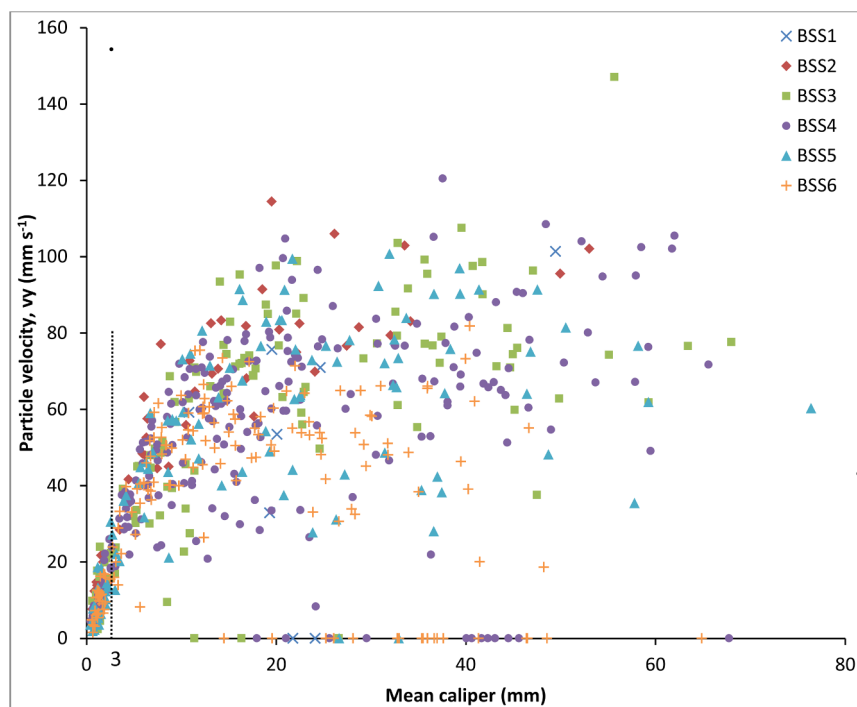


**Fig. 3.** Particle velocity characterised discretely for each particle and related to the particle mean caliper. Each particle is also segregated by Bristol Stool Scale (BSS) classification, as an indication of its structural composition. Zero velocity represents floaters.

matrices (Michaelides and Feng, 2023; Tran-Cong et al., 2004). A mean caliper of 3,000  $\mu\text{m}$  relates to  $\text{Re}_p \sim 20$ , and so the smaller particles below this threshold are within the Stokes and early intermediate flow

regime, where viscous forces dominate the drag effect and the faecal particles behave similarly to the hard-sphere model (Clift and Gauvin, 1971). The BSS descriptor for each discrete particle population may be

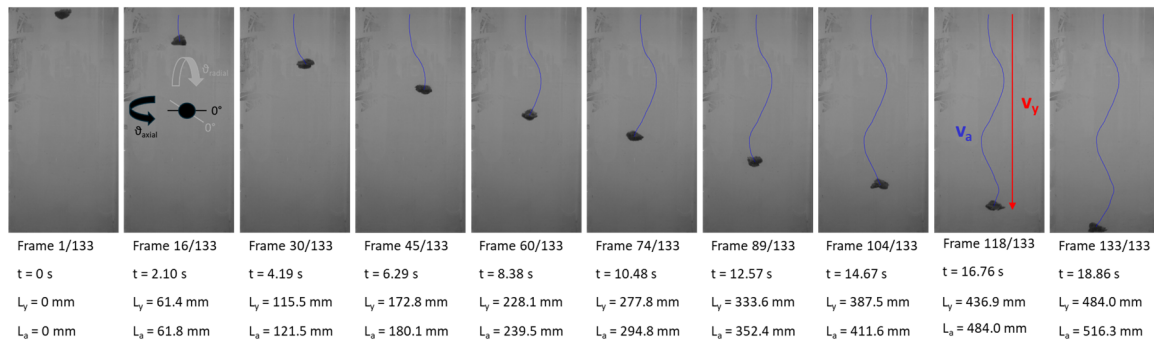


**Fig. 4.** Digital imaging used for determining the ‘actual’ settling velocity along the mean free path of the particle ( $v_a$ ) for comparison with the apparent settling velocity ( $v_y$ , in the y-plane). Data analysis for particle tracking was performed using imaging software (ImagePro Premier, v9.1, Media Cybernetics Inc., Maryland, USA). Larger particles rotate axially and radially during settling which introduce different path lengths between the straight downwards y-direction ( $L_y$ ) and the actual path of the particle ( $L_a$ ) leading to differences in settling velocity:  $v_a$  being the velocity of the particle along its own path, and  $v_y$  being the ‘true’ settling velocity, the speed at which the particle travelled in the y-direction. The extent of particle rotation can be more clearly observed in the supporting video footage, which is provided in supplementary information.

used to infer how structural differences inform settling beyond this threshold. For example, at an equivalent mean calliper, particles characterised as BSS6, which tend toward a mushy consistency (indicative of inflammation), generally settle slower as indicated by their bias toward the lower bound of the dataset. This is consistent with the fractal nature observed within this particle group, which is known to introduce greater drag (Takagi et al., 2019). Conversely, for an equivalent mean calliper, the particle population characterised as BSS2, which are of lumpy solid consistency (indicative of constipation), generally settle faster as indicated by data distributed toward the upper bound of the dataset. Due to the increased solids concentration, particles within this population tend toward a lower fractal dimension, where settling behaviour may be more analogous to solid objects of equivalent dimension which favours higher settling velocities (Guo et al., 2009; Moruzzi et al., 2020). While this is also characteristic of BSS1, the increased tendency toward constipation reduced particle size for this classification and as such, very few BSS1 particles comprise of larger mean callipers. A settling velocity of zero was recorded for a subset of particles, with representation from each BSS, which is indicative of floating. Recent literature provides a causal link between gas productivity of the gut microbiota and the formation of ‘floaters’ (Aalam et al., 2022). In this study, this phenomenon was only observed in samples exceeding a mean calliper of 11,000  $\mu\text{m}$ , where the higher probability for gas entrapment provides sufficient lift force to disrupt natural and effective settling (Bagheri and Bonadonna, 2016) and makes the derivation of specific density measurements for each particle particularly challenging. This is complimentary to observations in sludge settling, where gas-trapped particles or particles with irregular geometries introduced variance in settling velocities (Guo et al., 2009).

Particle geometry was analysed, as irregular geometries are known to introduce rotational and lateral movements during descent which can modify settling velocity (Tran-Cong et al., 2004; Guo et al., 2009; Michaelides and Feng, 2023). Frame-by-frame particle tracking was introduced, which enabled measurement of the ‘actual’ path length, incorporating the lateral movements across the x-plane, to provide a modified settling velocity (Fig. 4). This permitted the decoupling of changes to particle composition, which primarily lead to a modification of the settling velocity in the y-plane (for an equivalent particle), to those that alter settling velocity through geometric form (Fig. 5). A normalised settling velocity is therefore introduced which compares ‘actual’ settling velocity measured along the mean free path of the particle ( $v_a$ ) with that of the apparent settling velocity ( $v_y$ , in the y-plane), where a value of  $<1$  indicates the extent to which a specific geometric descriptor (mean calliper, aspect ratio, and circularity) may alter settling velocity. Particles with mean calliper values  $<20,000 \mu\text{m}$  consistently exhibit normalised velocities approaching 1.0, indicating a

linear particle trajectory. However, above this value, larger particles are observed to deviate from a linear path due to the interplay of increased drag forces, turbulent wake effects and orientation changes during settling (Michaelides and Feng, 2023). A key observation is that whereas distinctions in data distribution between BSS classifications was evident when analysing the particle population by settling velocity (Fig. 2), such discrimination is more challenging when characterised by normalised velocity. This suggests lateral movement may be more dominated by size and shape characteristics, rather than other morphological differences that differentiate faecal particles into their respective BSS classification. To interrogate the role of particle shape, aspect ratio ( $A_r$ ) and circularity were also examined (Fig. 5 b,c). The aspect ratio is a measure of particle elongation, which is pertinent to the classification of faecal particles due to their innate form. Particle elongation was evidenced to induce greater lateral movement during settling ( $A_r > 2$ ). This was particularly evident for particles classified as BSS3 and BSS4, which tend to be more cylindrical in form. For faecal particles, aspect ratio can be considered as the reciprocal of circularity, as aspect ratio is calculated from the major and minor axes of an ellipse equivalent to the particle area. Particles that were more circular in form were subject to considerably less lateral movement ( $v_y/v_a \sim 1$ ). This is of relevance as particles with minimal elongation (e.g. BSS1) may exhibit settling characteristics more proximate to those of a sphere, resulting in more symmetrical drag and flow conditions. It is the larger particles which predominantly combine the effects of shape and size on settling behaviour. This is analogous to previous observations which emphasise larger particles to be more susceptible to external disturbances that introduce deviations from theoretical settling behaviour (Bagheri and Bonadonna, 2016; Dietrich, 1982; Guo et al., 2009).

### 3.2. Relating particle characterisation to particle hydrodynamics during settling

The coefficient of drag ( $C_D$ ) was estimated for each particle as an indication of its resistance to flow, being dependent upon whether the fluid surrounding the particle is laminar or turbulent (Fig. 6a). Within the Stokes’ regime,  $C_D$  is at a maximum, since the flow remains attached to the particle, and as a result, the drag is dominated by viscous stresses (friction drag) (Bagheri and Bonadonna, 2016). The coefficient of drag continued to decrease for particles within the early stage of the intermediate regime up to  $Re_p \sim 20$ , which corresponds to the onset of flow separation (Clift and Gauvin, 1971). After  $Re_p \sim 130$ , the decrease in  $C_D$  with an increase in particle Reynolds number was comparably small, and the absolute value tended toward unity. This marks the commencement of vortex shedding, where wakes behind the particle become increasingly unstable (Bagheri and Bonadonna, 2016).

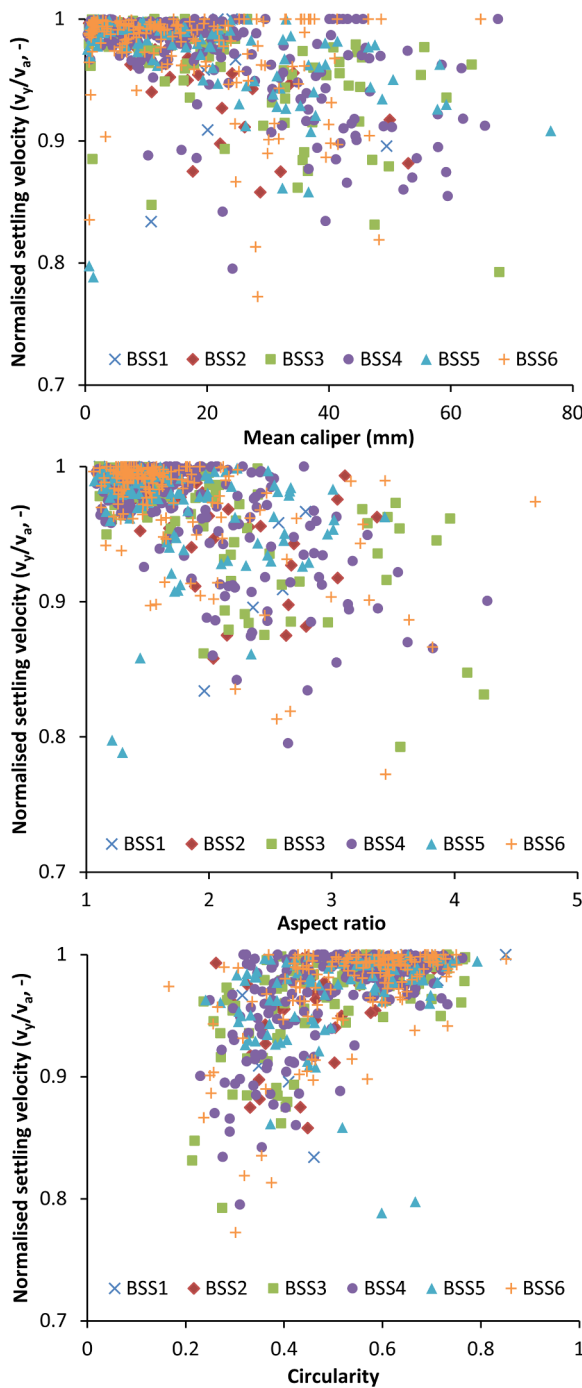


**Fig. 5.** Determination for how particle shape and particle size introduce lateral particle movement during settling. The normalised settling velocity compares 'actual' settling velocity along the mean free path of the particle ( $v_a$ ) with the apparent settling velocity ( $v_y$ , in the y-plane), where  $<1$  indicates transgression from the y-plane during settling: (a) size; (b) aspect ratio; and (c) circularity.

While a small number of particles were identified within the laminar regime (Stokes' regime), most particles were situated within the intermediate and turbulent flow regimes. This is distinct from most wastewater applications which typically deal with smaller biological aggregates (or flocs) with settling that primarily corresponds to Stokes' regime. Consequently, the size distribution of human faeces will tend to favour lower drag coefficients, and hence faster settling. However, the coefficient of drag for a falling non-spherical particle is higher than a spherical shaped particle (Bagheri and Bonadonna, 2016) (Fig. 6b). This

can hinder settling within the larger size particle population identified in this study, since migration away from sphericity has also been observed to be a function of particle size. This was illustrated through application of the hard sphere model from Clift and Gauvin (1971), which provides reasonable approximation to the lower bound of the dataset until flow separation commences ( $Re_p \sim 20$ ). A small number of samples with low  $Re_p$  lie close to, but below, the  $Re_p$  estimation provided by the hard-sphere model, which can be accounted for by the use of an equivalent diameter sphere which cannot directly reflect the complexity of non-spherical shapes. Importantly, the lower limit of the whole particle population (including this small particle population), can be well described by the Clift and Gauvin (1971) model, and is largely represented by particles characterised as BSS2 and BSS3, where small, hard particles of largely spherical shape are expected. After this threshold, wakes begin to form behind the particles ( $Re_p > 20$ ), and the error between the hard sphere model and the measured particle population increases. This error can be attributed to increased rotational effects and asymmetric drag, which disturb the settling process (Ganser, 1993; Michaelides and Feng, 2023). Elongated particles, similar to faecal particles, are more likely to experience tumbling or changes in orientation as they fall, experiencing higher drag and more chaotic settling patterns (Bagheri and Bonadonna, 2016). The general model for non-spherical solid particles of irregular and regular shape (Bagheri and Bonadonna, 2016), takes shape dependency into account. In analogy to Clift and Gauvin (1971), the Stokes term is largely unmodified as the reasonably uniform friction drag and reduced turbulence for small particles, makes for more predictable settling. However, the Stokes' and Newton's drag parameters that are incorporated to correct for shape dependency, provide a more definitive description of the lower bound across the complete dataset. The closeness of fit therefore confirms the significant role of faecal particle shape to settling behaviour, which the model can account for. The mean Stokes Form Factor,  $F_s$  of the current dataset was 0.060 (range 0.015 to 0.157) and the mean Newton Shape Descriptor,  $F_N$ , was 0.049 (range 0.006 to 0.153), demonstrating the non-spherical nature of faecal particles. It is suggested that the fitting of the model toward the lower bound of the dataset can be explained by its origin for the description of solid particles, which will experience lower drag than more porous aggregates. This is supported by the proximity of BSS2 particles which tended toward the lower bound of the dataset and are characterised as more compact and solid aggregates (Fig. 6b).

### 3.3. Estimating settling velocity from particle hydrodynamics

Due to the limitations of the hard sphere model (Clift and Gauvin, 1971), the estimated settling velocity is up to four times higher than the measured velocity (Fig. 7a). This overestimation is most pronounced for BSS3 to BSS5 which tend toward larger particle sizes, and greater elongation (or aspect ratio), due to the mechanical extrusion introduced by the human gut. The general model for non-spherical solid particles (Bagheri and Bonadonna, 2016) therefore provides a closer fit, particularly within the range of lower particle velocities, ostensibly due to the Stokes' drag correction parameter (Fig. 7b). However, the model continues to overestimate settling velocity for larger particles. Consequently, the original model proposed by Bagheri and Bonadonna (2016) is fitted to the dataset to empirically account for factors such as the fractal character and apparent density of the particles that cannot be easily quantified analytically but may contribute to the overestimation error observed. The Bagheri and Bonadonna equation (Eq. (6)) was expressed in full in Excel Solver, incorporating all its nested functions (Eq. (7) – 12), in order to optimise all of the component empirical constants for the current dataset. Each of the empirical constants were fitted to minimise deviation, with exception to Stokes' constant ( $24/Re_p$ ), due to its theoretical derivation and proximate fit to particle data under laminar flow (Eames and Klettner, 2017) (Eq. (13)):

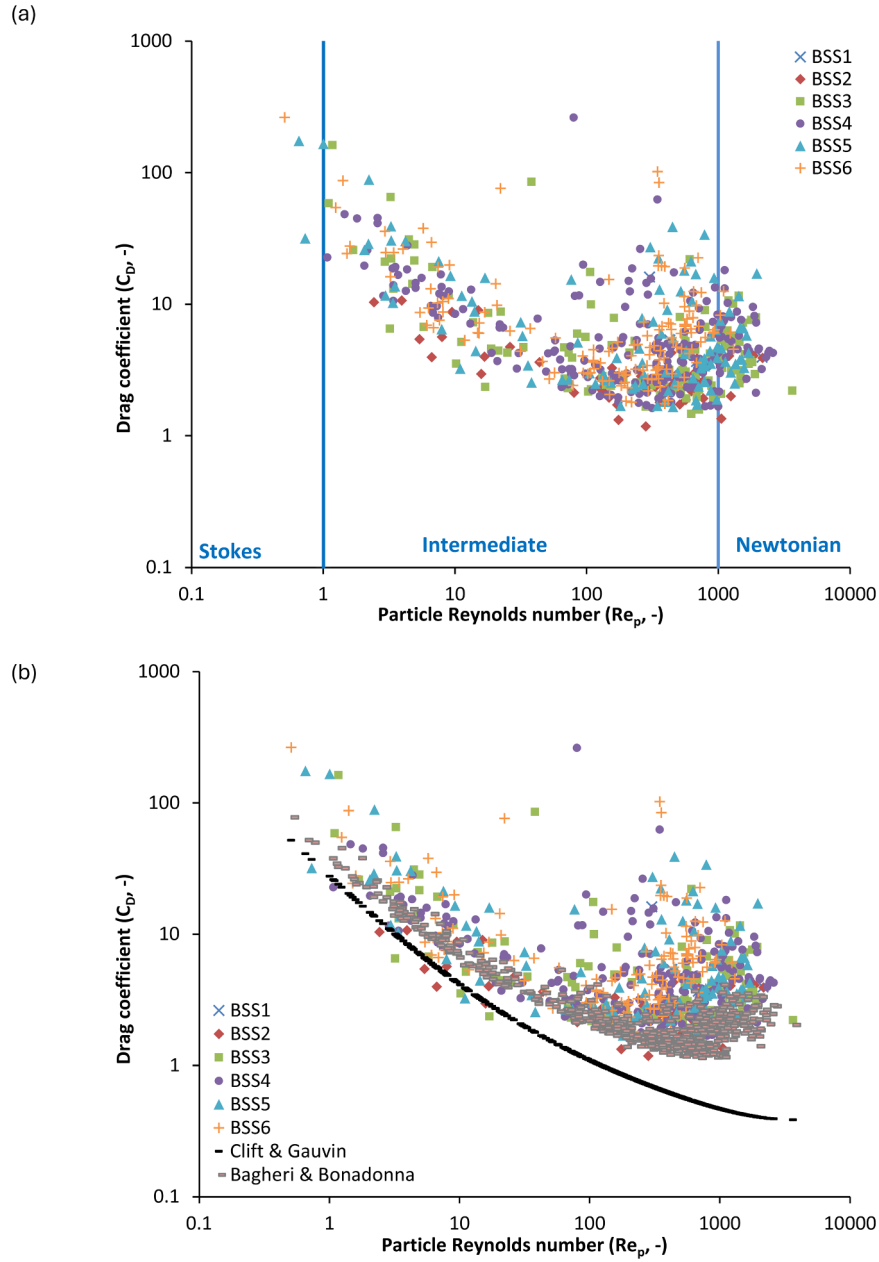


**Fig. 6.** Characterisation of the coefficient of drag (CD) for each fresh faecal particle measured: (a) Identification of the relevant flow regimes; and (b) comparison to the 'hard sphere model' (Clift and Gauvin, 1971), and 'non-spherical solid particle model that incorporates regular and irregular shapes' (Bagheri and Bonadonna, 2016).

$$C_D = \frac{24k_S}{Re_p} \left( 1 + 0.054 \left( \frac{Re_p k_N}{k_S} \right)^{1.04} \right) + \frac{-0.04k_N}{1 + \left( \frac{10.414}{\frac{Re_p k_N}{k_S}} \right)} \quad (13)$$

The shape dependent drag correction factors  $k_S$  (Eq. (7)) and  $k_N$  (Eq. (9)) were also fitted with modified constants (Eq. (14)):

$$k_S = \frac{(F_s^{-0.061} + F_s^{-0.004})}{0.72} \quad (14)$$

Where  $F_S$  (Eq. (15)) is refined from (Eq. (8)):

$$F_S = f e^{5.62 \left( \frac{d_{eq}^3}{L I S} \right)} \quad (15)$$

This modification results in a larger  $k_S$  value (mean 5.13 cf. 1.51 for

the original Eq. (7)), which fosters a closer data fit to this study's empirical data than the original term permits. Empirical constants were also fitted within the sigmoidal functions ( $\alpha_2$  and  $\beta_2$ , Eqs. (17) and (18)) of the Newton drag correction parameter which relate the relative density of the particle to the fluid (Eq. (16)):

$$k_N = 10^{\alpha_2 [-\log(F_N)]^{\beta_2}} \quad (16)$$

Where:

$$\alpha_2 = 0.04 + \frac{10}{\exp(2.5 \log \rho' + 30)} \quad (17)$$

$$\beta_2 = 1 - \frac{37}{\exp(-3.9 \log \rho' + 105)} \quad (18)$$

are refined from (Eq. (11)) and (Eq. (12)) respectively. As a result, the

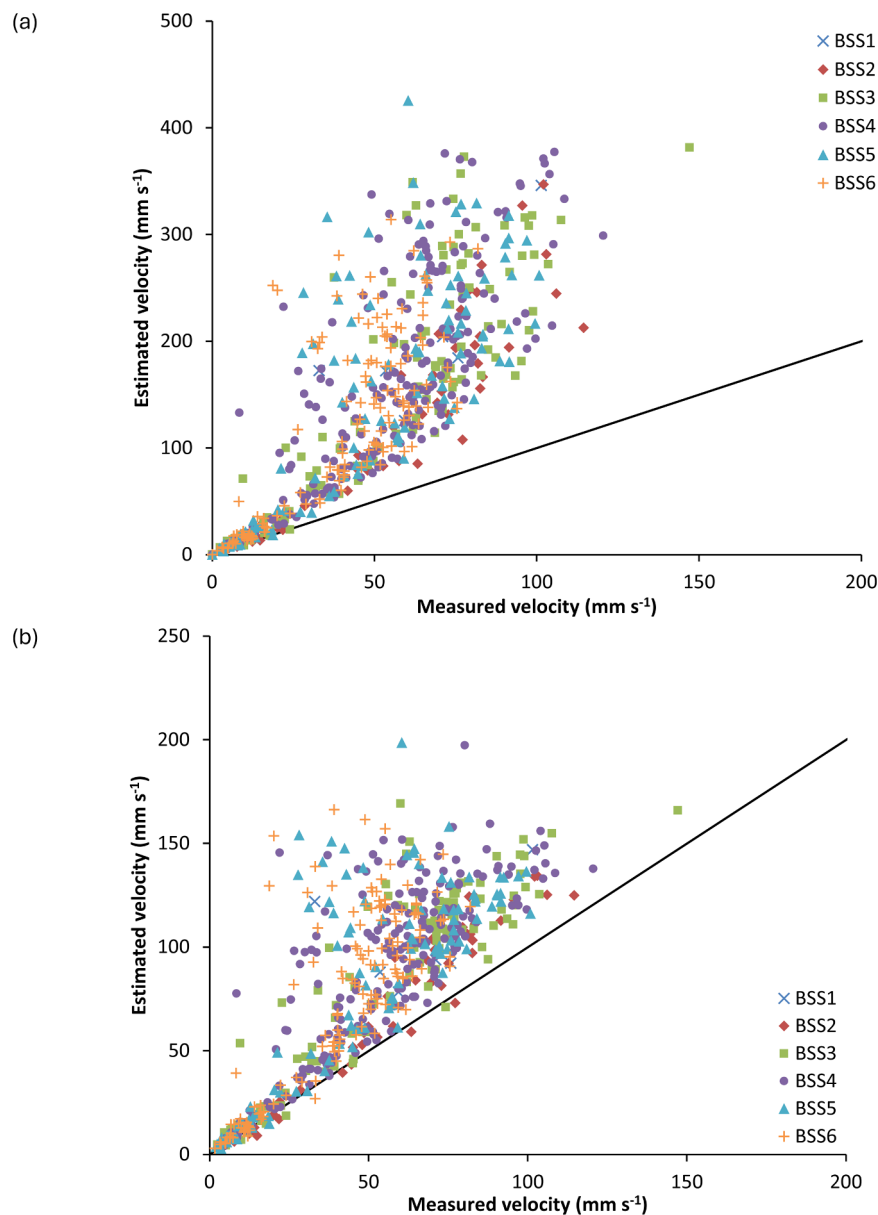


**Fig. 7.** Measured particle velocities and compared to particle velocities estimated with use of: (a) the 'hard sphere model' (Clift and Gauvin, 1971); and (b) 'non-spherical solid particle model that incorporates regular and irregular shapes' (Bagheri and Bonadonna, 2016). The black solid line indicates parity between measured and estimated data. Note the absolute values estimated in (b) more closely correspond to measured data than for the hard sphere model.

mean  $k_N$  value across the dataset is smaller compared to the  $k_N$  calculated from Eq. (9) (1.13 and 4.32 respectively). The subsequent term provides an estimation of  $C_D$  for faecal particles that provides a closer approximation of settling across each hydrodynamic regime (Fig. 8a). This yields a tighter data distribution for estimated settling velocity of faecal particles, where the estimated velocities more closely represent the measured particle velocity (as represented by the parity line), which can enable sizing for type 1 settling of fresh faecal sludge within solid-liquid separation unit processes, taking into consideration variance in particle settling imposed by gas entrapment amongst other atypical morphological factors specific to faecal particles (Fig. 8b).

### 3.4. Implications for the transformation of sanitation practice

Current sanitation practice does not make use of solid-liquid separation, which increases the sludge volume for pit emptying, and decreases flowability due to shear and aging effects, making fluid transport more challenging. The model proposed can satisfactorily describe fluid

particle settlement despite heterogeneity in particle size, shape and fractal character. This challenges the anecdotal application of the Bristol Stool Scale as a proxy indicator of settlement characteristics, providing analytical evidence that effective particle settlement can be achieved independent of particle character, with the potential to enhance solid-liquid separation. Faecal particles are considerably larger and denser than pit latrine sludge (<1000  $\mu\text{m}$ , Brouckaert et al., 2013) or sewage sludge (<100  $\mu\text{m}$ , Christensen et al., 2015). While this transitions particle flow characteristics into transitional and turbulent flows where inertial forces disrupt particle streamlines, fresh faecal particle settling velocities vastly exceed those of other sludges of human origin. Fresh faecal sludge can therefore be separated quickly in compact separation stages that could be instigated within the existing footprint of conventional latrine technology. Elongated faecal particles were particularly susceptible to tumbling and asymmetric drag forces, but this did not result in particle breakage (Figs. 4 and 5). We propose this is due to the applied shear stress being insufficient to overcome the compressive yield stress, which is a facet unique to fresh faecal particles owing to their

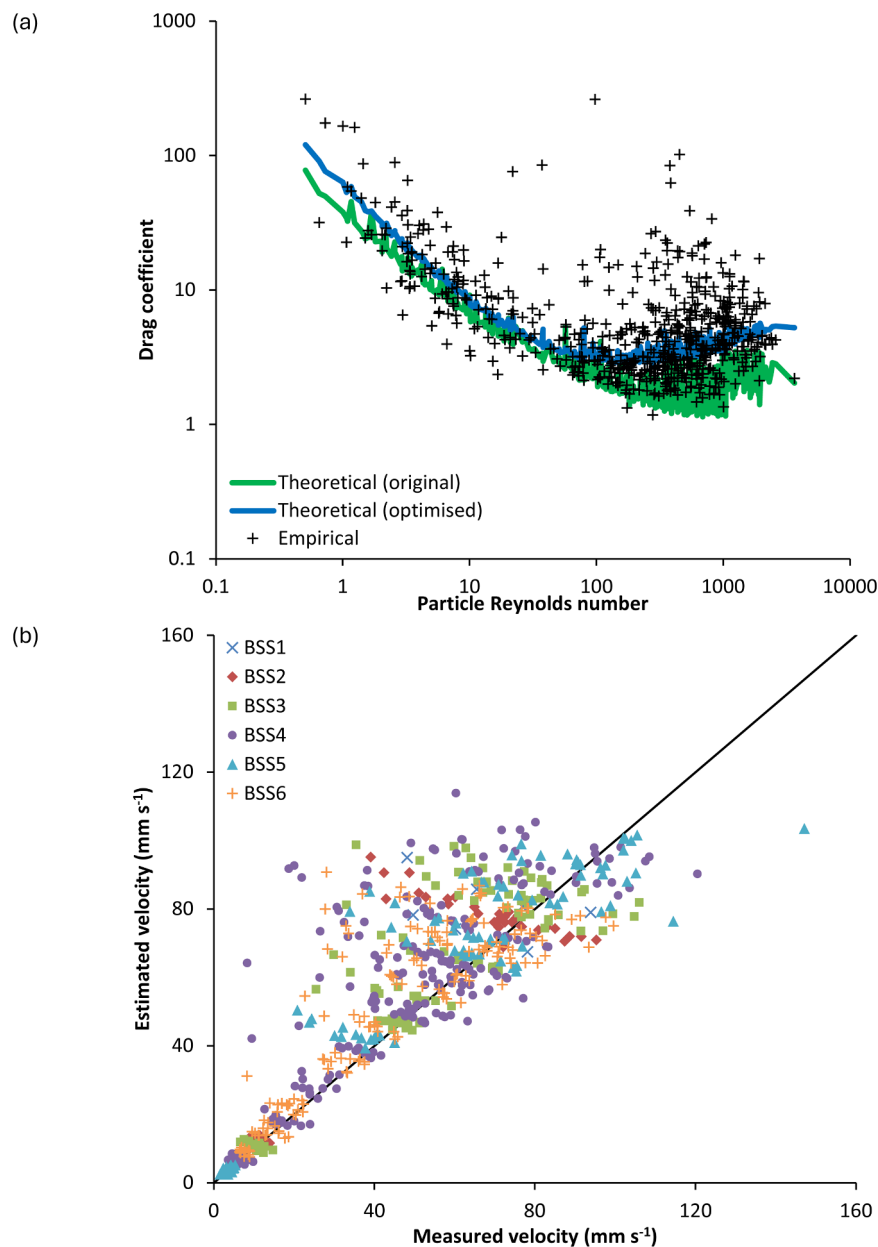


**Fig. 8.** Regressive fitting of the empirical data is used to modify the ‘non-spherical solid particle model that incorporates regular and irregular shapes’ (Bagheri and Bonadonna, 2016) to improve description of free falling fresh faecal particles: (a) comparison of the coefficient of drag based on the original constants and those fitted using regressive technique; and (b) estimated velocity based on the regressive fitting of Bagheri & Bonadonna (2016). The black solid line indicates parity between measured and estimated data. Note the absolute values estimated in (b) are lower than for the original model, and more closely grouped.

compression and dehydration in the colon (Lewis and Heaton, 1997). The significance is the capability for effective faecal particle capture in solid-liquid separation which can yield a high solids underflow with favourable rheological properties that minimises transport volume and pumping complications that could transform the economics of pit emptying.

#### 4. Conclusions

The key implications of this study can be summarised as follows:

- An analytical solution has been provided to describe the hydrodynamics around faecal particles that can estimate settling for this complex particle suspension whose specific morphological properties are notoriously difficult to quantify (e.g. density, fractal dimension). Further refinement of this solution could be provided through developing techniques capable of refining particle density estimation through disaggregating the solids fraction from gas driven buoyancy effects.
- A strong relationship exists between the particle calliper and the settling velocity for particles smaller than 3000  $\mu\text{m}$ , where hydrodynamics are best described by viscous forces. The early phase of this flow regime is characteristic of that employed for the description of type 1 settling in centralised municipal sewage treatment works, where median particle sizes tend toward the minimum observed for faecal particles.
- Above this 3000  $\mu\text{m}$  particle size, differences in settling velocity could be related to morphological differences, through classification by the Bristol Stool Scale, from which the role of fractal character and particle density can be qualitatively reasoned.

- However, within this particle size range where inertial forces primarily govern hydrodynamic resistance, particle shape and particle size were perceived as more critical to the measured settling velocity. This was emphasised by an improvement in the estimation of the coefficient of drag when adopting the non-spherical model versus the hard sphere model.
- Through empirically fitting the non-spherical model to the experimental data within this study, the intricate interactions between fractal morphology and apparent density are also considered, permitting an improvement to the estimation of faecal particle hydrodynamics specifically. Settling velocity can thus be estimated more accurately, particularly at the upper bound of the dataset.
- The work provides evidence for reasoned discussion regarding the deployment of localised solid-liquid separation for the betterment of economic and safe sanitation.

## CRediT authorship contribution statement

**R.T. Mupinga:** Writing – review & editing, Writing – original draft. **S. Usher:** Writing – review & editing. **B. Jefferson:** Writing – review & editing, Supervision. **Y. Bajón Fernández:** Writing – review & editing, Supervision. **E. McAdam:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **P.H. Cruddas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: P. H. Cruddas reports financial support was provided by Bill & Melinda Gates Foundation. R.T. Mupinga reports financial support was provided by EPSRC Centre for Doctoral Training - Water WISER. R.T. Mupinga reports financial support was provided by Water for People. If there are other authors, they 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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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.watres.2026.125759](https://doi.org/10.1016/j.watres.2026.125759).

## Data availability

Data is now available in supplementary information

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## **Characterising faecal particle settling hydrodynamics to reenvision solid-liquid separation in decentralised sanitation systems**

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