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Experimental investigation of segregation in a rotating drum with non-spherical particles

Sunil Kumar, Salma Khatoon, Jeetram Yogi, Sanjay Kumar Verma, Anshu Anand *

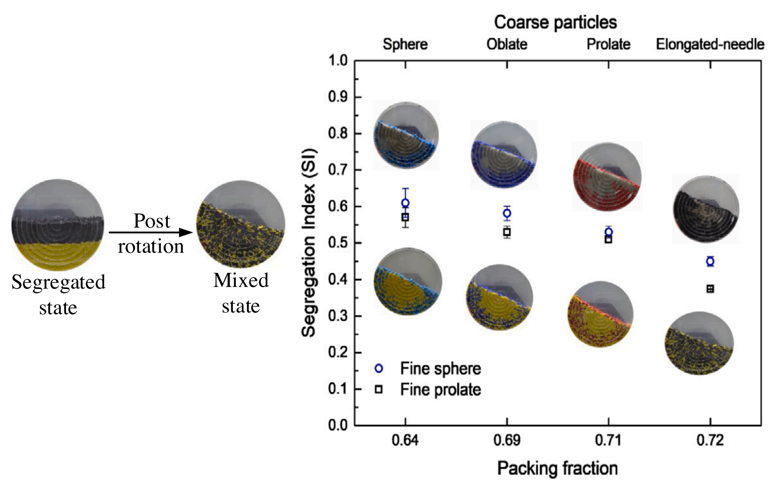
Department of Chemical Engineering, Indian Institute of Technology, Roorkee, 247667, Uttarakhand, India

HIGHLIGHTS

- Coarse particles with higher mono-dispersed random packing density promote mixing.
- For coarse particles segregation pattern: Sphere >oblate >prolate >elongated needle.
- The fine particles with greater angularity promote mixing.
- For fine particles segregation pattern: Sphere >cube >prolate.

GRAPHICAL ABSTRACT

Particle shape-induced segregation in a rotating drum



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ABSTRACT

The focus of the current investigation is to study the influence of particles' shape on segregation of bi-disperse mixture of particles in a rotating drum. The effects of various particle parameters such as shape, size, density and size ratio are investigated along with system parameters like time, rotational speed. The results show the shape of both coarse and fine particles influence mixing. For the coarse particles, decreasing trend of extent of radial segregation as follows: sphere > oblate > prolate > elongated-needle. For the fine particle, the trend follows as sphere > cube > prolate. These trends are strongly correlated to the mono-dispersed random packing density and particle angularity. The result shows that coarse particles with higher mono-dispersed random packing density show less segregation whereas fine particles with greater angularity improves mixing. Segregation can be controlled in multiple scenarios in industries by choosing the appropriate shape of the particles.

1. Introduction

A rotating drum is a relatively simple, low-cost equipment widely used in various industries. Some specific examples include ball mill operation in paint and cement industry [1], production lines for powders [2], kiln in cement industry [3], blender in numerous industries such as food, cement, refractory material, fertiliser and glass ceramics industry. Rotating drums feature a number of technological

* Corresponding author.
E-mail addresses: skumar11@ch.iitr.ac.in (S. Kumar), anshu.anand@ch.iitr.ac.in (A. Anand).

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Nomenclature

Notation

Δr	Drum's section width [L]
Ω	Rotational speed [T^{-1}]
L	Drum's length [L]
N	Number of samples [-]
R	Drum's radius [L]
RPM	Rotation per minute [T^{-1}]
SI	Segregation index [-]
VFD	Variable frequency drive [-]
x_i	Fines mass fraction of a given section of sample [-]
x_o	Total fines mass fraction of initial load [-]
r_i	Radial position of sample cell [L]
x_{ps}	Represents a binary mixture; with subscripts representing shape of the particles: First subscripts represents the shape of coarse particle and second subscripts represents the shape of fine particle [-]

Mixture subscripts

E	Elongated needle
O	Oblate
P	Prolate
S	Sphere
W	Wheat

advantages over other systems like vibrated packed bed and fluidised bed mixer that include good mixing behaviour, a simplistic structure, easy sanitisation, and an immense handling capacity [4].

In particle technology, the phenomenon of segregation is considered the opposite of mixing and naturally occurs in various flow situations. Quantifying segregation is crucial for the blending process. Segregation can cause multiple problems such as non-uniform pharmaceutical formulation, poor concrete preparation, unmixing of dry fruits in the food industry, caking formation in the detergent industry and inconsistent discharge rate from hopper [5]. For instance, in the pharmaceutical industry, fluctuating composition of the active pharmaceutical ingredient (API) due to segregation can lead to varying dosage during blending operations.

In a rotating drum, it is observed that both radial and axial types of segregation can occur [6,7] and the efficiency of particle segregation in a rotating drum is function of certain variables, such as particle size, particle density, friction coefficients, filling degree, and rotation velocity [8–12]. Santos et al. [13] use the image analysis technique to transform the colour image into 8-bit greyscale, black, and white pixels using Image J software and quantify the segregation index by counting the number of particles in each section cell. Similarly, to calculate radial segregation, Hajra and Khakhar [14] use image analysis techniques in Image Pro Plus to analyze red and green colours in multiple images. Nakagawa et al. [15] investigates radial and axial segregation in a horizontal rotating drum using the nuclear magnetic resonance imaging (NMRI) approach. The results show that radial segregation develops prior to axial particle movement where the smaller particles migrate in between the coarse particles (axial segregation). Three bands are observed axially in which the smaller particle is entrapped in the larger particle. Barczi et al. [16] investigate axial segregation in a rotating drum and observe that the aspect ratio and initial particle concentration influence the evolution of complex spatio-temporal patterns along the length of the drum. Hlosta et al. [17] use DEM simulation to optimise a number of parameters, including shape, size, and density, with the help of various calibration techniques such as the discharge test, piling test, and static and dynamic angle of repose test. When results were compared to actual experiments, the study suggests that the piling test produces the most accurate results compared to other techniques. The results suggest that in order to produce more accurate results during the angle of repose calibration test, the test must be performed with approximately 4000 particles and a drum to particle ratio greater than 25.

Earlier the majority of the research focused on spherical particles [18]. However, in the current decade, non-spherical particles account for most of the studies. There are several computational modelling work on the mixing processes in a rotating drum [19–21]. Most of the real industrial particles are non-spherical which makes computational work more challenging due to the difficulty of contact detection [22,23]. Examples of non-spherical particles include catalysts, powder, pharmaceutical tablets, grains etc. Chen et al. [24] suggests the use of nano and micro non-spherical particles for drug delivery since non-spherical particle shape improves drug delivery efficiency compared with spherical ones. In a rotating drum mono-dispersed particles have higher velocities of the active layer than polydisperse particles [25].

Lu et al. [26] state that radial segregation can be induced solely by particle shape and concludes that segregation occurs due to differences in particle mobility; non-spherical particles collide more frequently than spherical particles, resulting in lower mobility of non-spherical particles [27]. A simulation study with discrete element method (DEM) at different rotations per minute (RPM) such as 25, 30, and 40 RPM shows that aspect ratio of 0.5 (oblate) and 2 (prolate) give a better mixing rate than aspect ratio of 1 (sphere) [28]. This is due to superior flowability of sphere. The spherical-shaped particle mixtures are more difficult to mix than irregularly shaped particles [27]. Piacenza et al. [29] reports that the segregation intensity increases with increase in the difference in aspect ratio between the particles. Particles with larger aspect ratio tend to accumulate at the centre, while particles with lower aspect ratio move to the periphery of the drum.

With a unique solidifying bed sampling approach, Yari et al. [30] investigate the size segregation and conclude that the percolation mechanism takes place for size ratios less than 0.2, causing fine particles to percolate to the centre of the drum. For unequal size particles with varying volume fractions of bi-disperse mixture in a rotating drum, Dury et al. [31] observe that the best mixing is accomplished if the filling height is slightly greater than a half-filled drum. Chung et al. [32] experimentally examine the effect of fine particle concentration on a mixture of different sizes and conclude that adding a small amount of fine promotes size segregation which influences the dynamic properties of the mixture. Eskin et al. [33] study size segregation in a rotating drum numerically and observe that the difference in size between particles is one of the most important parameter that causes segregation and the smaller difference in particle sizes results in the higher mixing rate. Kumar et al. [34] examine the change in the bulk properties of bi-disperse granular particles by taking small amount of fines and observe that particle size distribution influences the bulk properties of the mixture like packing fraction and bulk modulus.

Yamamoto et al. [35] examine density segregation and report that particles with a lower density flow relatively easily than those with a higher density and recommend introducing lifters to reduce the relative velocity between coarse and fine particles to promote mixing. The true density has a greater impact than cohesive forces during axial dispersion of particles [36]. Ji et al. [4] observe that the spherical particles have a low mixing rate compared to cubes and cylinders, and the trend of mixing rate follows as cube > cylinder > sphere. Another key finding is that the mixing rate increases as the aspect ratio deviates from 1.0. Along with material properties, system parameters such as rotational speed affect mixing. Hou et al. [37] use the image analysis technique to identify a relationship between the lacey mixing index and time and argue that in rolling regime mixing increase with an increase in rotational speed until it surpasses a certain critical level.

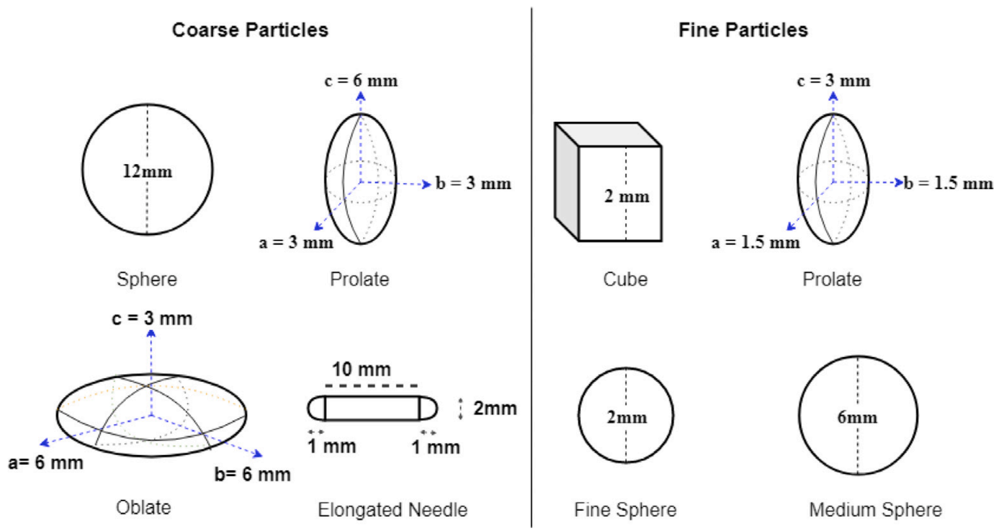


Fig. 1. Schematic diagram of particle used.

In the current work, non-spherical particles are mixed with spherical particles to form multiple binary mixtures and a segregation index is used to characterise segregation in each case. Various system and particle parameters are investigated that include the effect of time, rotation speed, section width, loading, shape, size, density, size ratio, fine particle concentration. Novel experimental data is generated using different types of non-spherical particles which include cube and elongated needle. We anticipate that this exhaustive data will be extremely relevant in characterising the flow of real particles used in multiple fertiliser and pharmaceutical industry. A significant aspect of this study is that it bridges the gap between scientific theory and industrial practice by considering non-sphericity of the particle. The interactions between non-spherical particles are considered and compared to well known results of the spherical case. Thus, providing critical insight about change in flow behaviour and its effect on segregation as we consider the non-sphericity of the particles.

2. Background

In this section, we discuss the particle used in the experiments, the experimental setup, and the methodology used to quantify the extent of segregation.

2.1. Particles used

Engineered as well as naturally occurring material (i.e., wheat) are used to study the segregation behaviour of particles in a rotating drum. All engineered particles are made up of glass (non-cohesive) and consist of spherical and non-spherical particles. These particles are custom designed and manufactured for these experiments. Glass particles are chosen because they are inexpensive and readily available. It can be customised into different colours for clear visualisation. The Fig. 1 depicts a schematic diagram of the particle used in this work, and Table 1 illustrates the material properties of the particles used in the experiments. Feret length is defined as the maximum distance between two parallel tangents of opposite edges of the particle. Larger particles with a 12 mm in feret length are considered coarse, whereas smaller particles with 2 mm feret length are considered fine. Fig. 2 shows the actual image of various particles used in this study. Two distinct shapes in a predetermined mass ratio of particles are poured in a drum and the drum is rotated to study the behaviour of radial segregation of the binary mixture.

Table 1
Material properties of particles.

Particles	Mean radius (mm)			Average mass	Average density	Sphericity (Φ)
	a	b	c	(g)	(kg/m^3)	–
Coarse sphere	6	6	6	2.442	2500	1
Coarse prolate	3	3	6	0.662	2500	0.93
Coarse oblate	6	6	3	1.360	2500	0.91
Coarse elongated needle	1	1	6	0.128	2500	0.69
Medium sphere	3	3	3	0.262	2500	1
Fine sphere	1	1	1	0.011	2500	1
Fine cube	1	1	1	0.027	2500	0.81
Fine prolate	1.5	1.5	3	0.099	2500	0.93
Wheat	1.5	1.5	3	0.051	1250	0.93

2.2. Experimental set-up

The setup consists of a circular drum with an inner and outer diameter of 290 mm and 300 mm. The length of the short drum is 50 mm. Drum length is kept short so that the effect of axial segregation can be neglected. Drum is connected to a motor through a shaft. The drum is made up of an acrylic sheet and drum's faces were made transparent to capture particle snapshots through a video recorder. Rotation of the drum is controlled by a variable frequency drive (VFD). All experiments were captured using a digital camera (NIKON D5300). Fig. 3 shows the schematic diagram of the rotating drum with a variable frequency drive to control rotations per minute (RPM).

2.3. Methodology

Two different types of particles are chosen based on the parameter to be studied. Selected particles are slowly poured into the drum. One of the particles is coarse, while the other is fine. In the bed, one type of particle is placed over another type of particle. Together, the mass of coarse and fine particles will determine the bed fill height. Energy to the particles is provided by means of rotations through the drum. Post-rotation, the settled bed of particles is subdivided into thin radial sections with the help of a separator, and samples are collected from 9 distinct sections, as shown in Fig. 4. After then, each of the thin segments is examined separately for the constitution of particles by sieving them individually. Collected samples are then further analysed for segregation data.

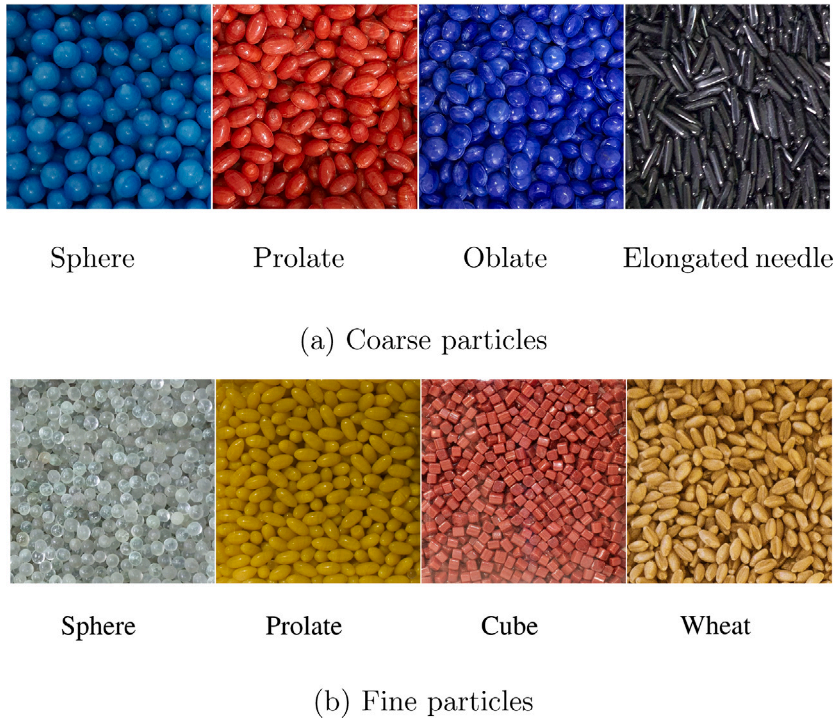


Fig. 2. Particles used in the experiments.

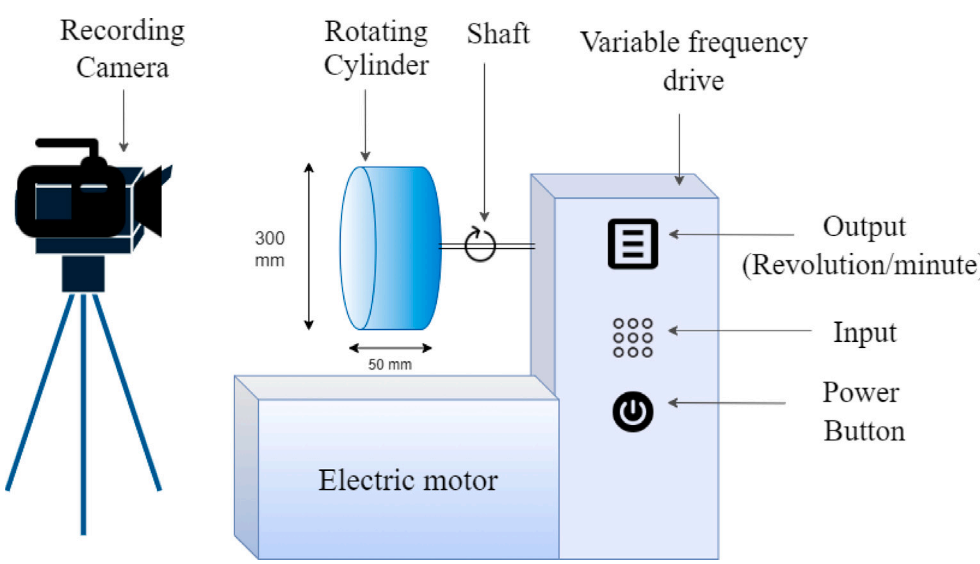


Fig. 3. Schematic diagram of the rotating drum experimental setup.

Segregation index (SI) a factor calculated to evaluate the overall radial segregation of the entire drum [26,38–41], as shown in Eq. (1). The fines mass fraction in a particular mixture is x_i, while the overall fines mass fraction in the initial load is x_o. Normalised fine mass fraction which is the ratio of x_i by x_o, is calculated for each section. For the equal mass ratio of the fine and coarse particle in the initial load, the corresponding value of x_o is 0.5. If there is no radial segregation in a drum, the value of normalised fine mass fraction remains constant and equal to 1, and any variation from this value indicates demixing (see Eq. (2)). Throughout this study, the single parameter, i.e., Segregation Index (SI), is used to analyse and evaluate the extent of segregation for all the parameters studied. In a mixture of particles, SI value equal to 0 represents complete mixing, whereas SI value equal to 1 represents complete segregation.

$$SI = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\left(\frac{x_i}{x_o}\right)_n - \left(\frac{x_i}{x_o}\right)_{mean}\right)^2} \tag{1}$$

For an equal mass ratio of fine and coarse particles;

$$\left(\frac{x_i}{x_o}\right)_{mean} = 1 \tag{2}$$

where, N = Number of samples

x_i = Fines mass fraction of a section of the sample

x_o = Total fines mass fraction of the initial loading

The average value of normalised fine mass fraction (x_i/x_o) is determined by repeating the experiments and sampling three times. In

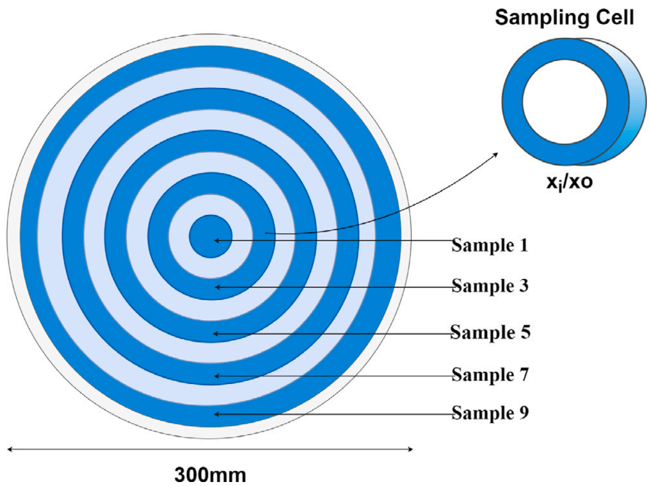


Fig. 4. Radial sampling and section cell.

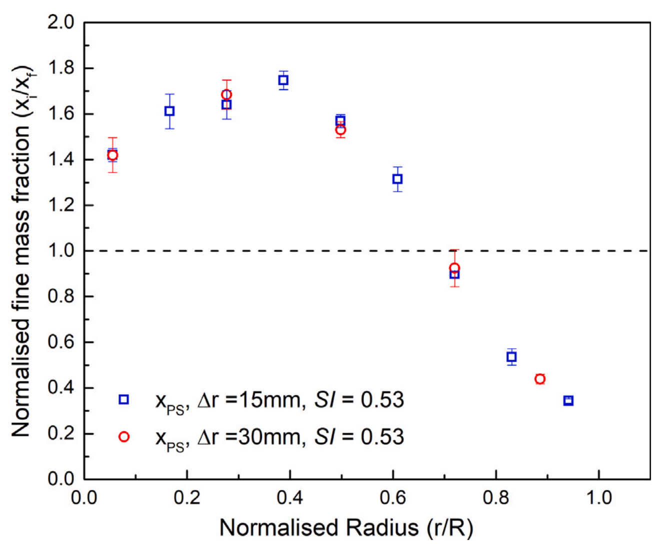


Fig. 5. Plot of normalised fine mass fraction versus normalised radius with different section widths. Process parameter = Initially coarse prolate are placed over fine sphere, time of revolution = 10 min and rotational speed = 5 RPM.

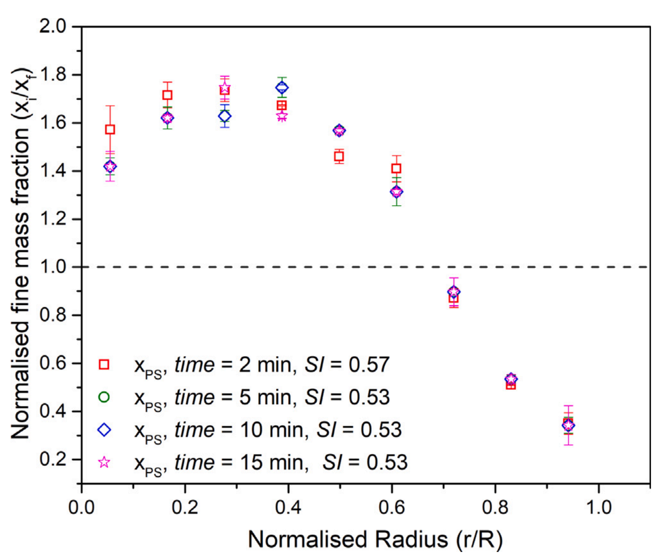


Fig. 6. Plot of normalised fine mass fraction versus normalised radius for different time values. Process parameter = Initially coarse prolate are placed over fine sphere and rotational speed = 5 RPM.

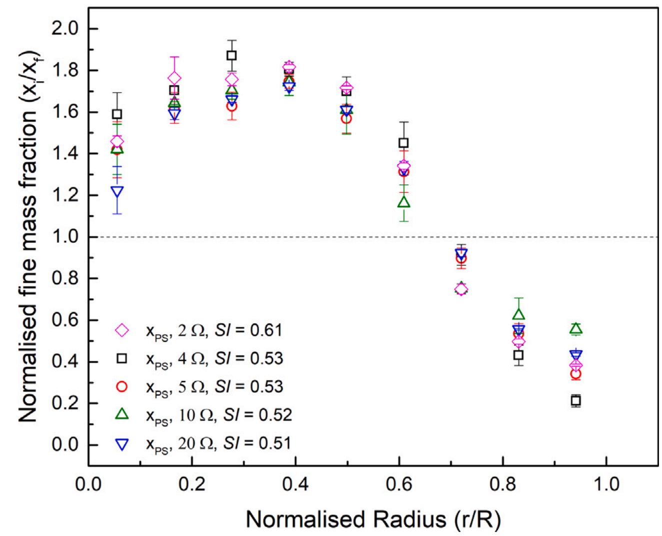


Fig. 7. Plot of normalised fine mass fraction versus normalised radius with increasing value of Ω. Process parameter = Initially coarse prolate are placed over fine sphere, time of revolution = 10 min.

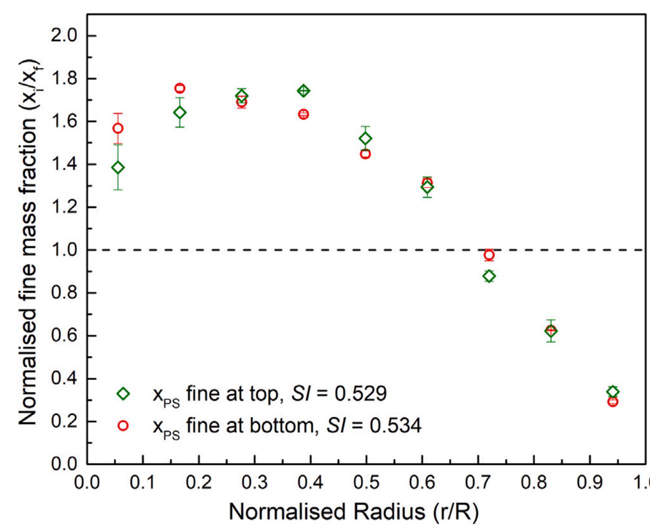


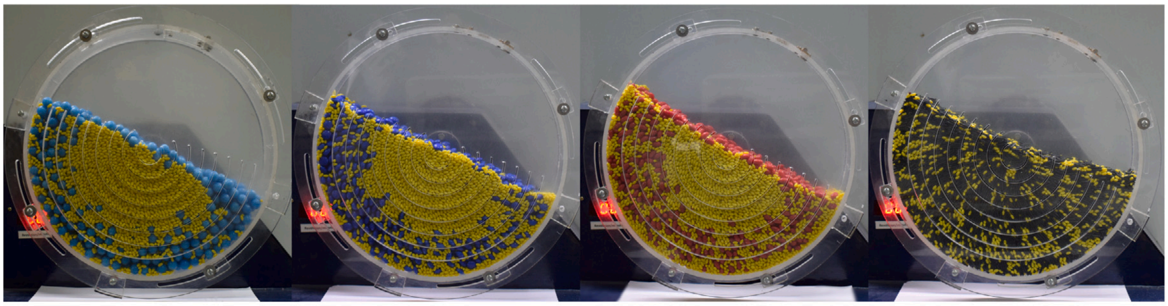
Fig. 8. Plot of normalised fine mass fraction versus normalised radius for different configurations of particles in a system. Process parameter = Time of revolution = 10 min and rotational speed = 5 RPM.

any typical plot, 95 percent confidence intervals are plotted from these three distinct experimental runs.

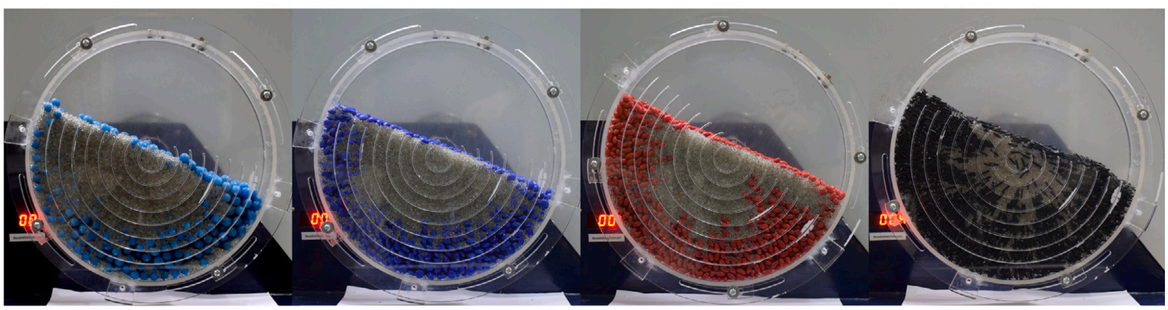
3. Results and discussion

This section describes the influence of system and particle parameters on overall extent of radial segregation in a rotating drum. System parameters include time, rotations per minute (RPM), section width and solid loading whereas particle parameters include shape, size, and density. Radial samples are obtained after the drum has rotated for a certain period of time. The segregation index is quantified by plotting the normalised fines mass fraction against the normalised radius. To investigate the influence of various particle and system parameters, values are varied from the base case in all experiments.

In this work, x represents the mass fraction. x_{PS} represent a bulk mixture in which the first subscript denotes shape of coarse particles whereas second subscript denotes shape of fine particles. For example, if the mixture is denoted by the subscript PS, it would represent that the



(a) Different coarse particles with fine prolate.



(b) Different coarse particles with fine sphere.

Fig. 9. Actual image of bi-disperse system with different coarse particles.

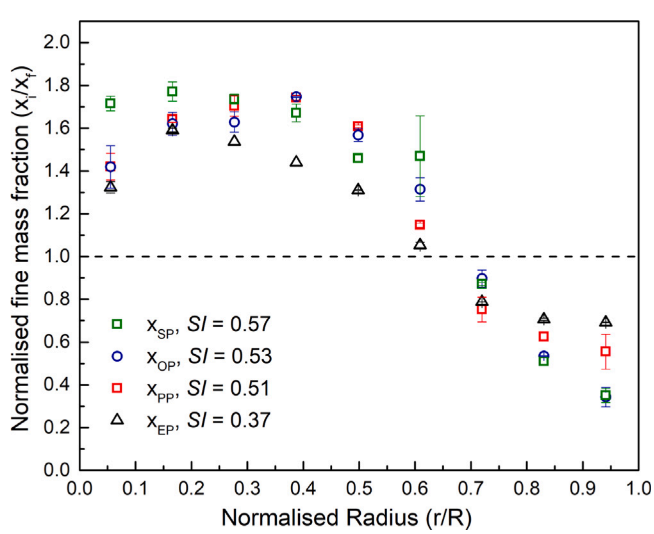


Fig. 10. Plot of normalised fine mass fraction versus normalised radius for different coarse particle shapes with fixed fine prolate. Process parameter = Initially coarse particle are placed over fine prolate, time of revolution = 10 min and rotational speed = 5 RPM.

system is composed of coarse prolate with a fine sphere. x_{OP} represents a bulk mixture of coarse oblate with fine prolate. This notation will be used throughout work.

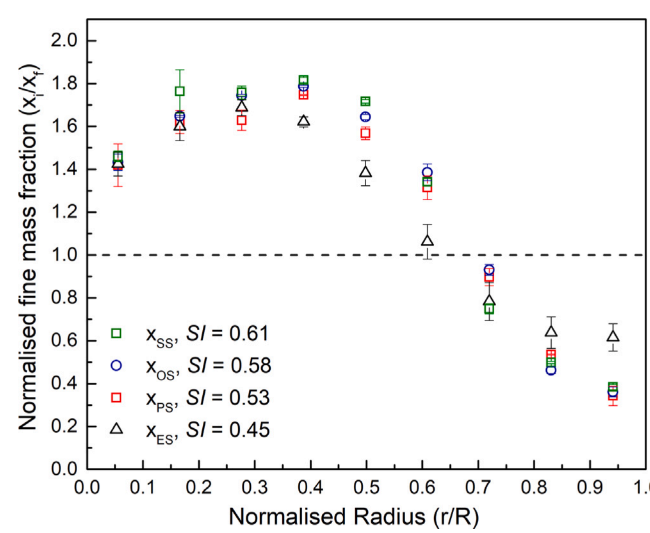


Fig. 11. Plot of segregation index versus normalised radius for different coarse particle shapes with fixed fine sphere. Process parameter = Initially coarse particle are placed over fine sphere, time of revolution = 10 min and rotational speed = 5 RPM.

3.1. Sensitivity study

Four different sensitivity studies are conducted to fix the base case, which include time study, section width study (Δr), rotations per minute (RPM) study and particle configuration study. In all the sensitivity analysis, coarse prolate with fine sphere is used.

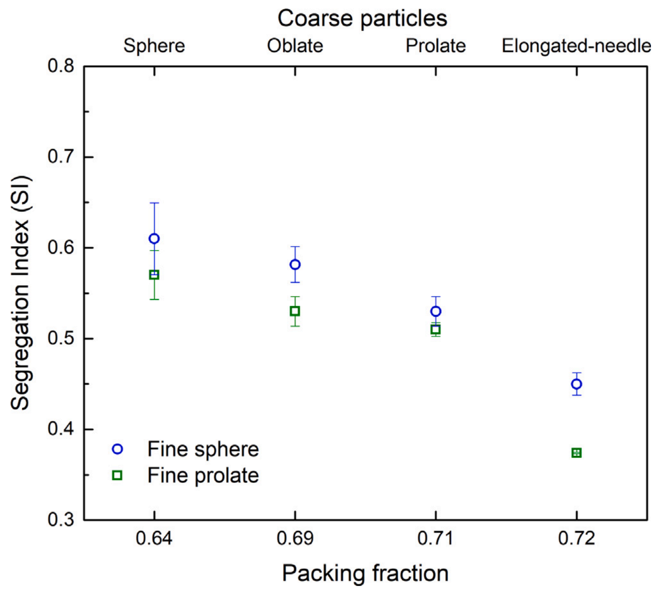


Fig. 12. Plot of segregation index with different coarse particle's shapes.

Table 2
The deviation of SI at different time values.

Time (Min)	SI	% Change in SI = $\frac{\lvert SI_{5minute} - SI_{xminute}\rvert}{Maximum(SI_{5minute}, SI_{xminute})}$
2	0.57	7.01%
5	0.53	Reference
10	0.53	0
15	0.53	0

3.1.1. Effect of section width

To examine the effect of section width on the extent of segregation, samples are extracted from two distinct section widths (Δr), i.e., 15 mm and 30 mm in the radial direction. The Fig. 5 shows, plot of the normalised fine mass fraction (x_i/x_o) against the normalised radius (r/R). Results indicate that there is no change in SI values when comparing section widths of 15 mm and 30 mm. The more concise the width of the section, the more detailed and in-depth the analysis of the segregation data. Hence, a section width of 15 mm is considered all through this work.

3.1.2. Effect of time

To examine the effect of time on extent of segregation, the drum is rotated for different times. Fig. 6 shows plot of normalised fine mass fraction against the normalised radius for four different time values. Previous results from Widhate et al. [42] and by Xiao et al. [41] shows that the rotating drum system will reach the study state quickly. This sensitivity study results suggest that 10 min is enough to get a steady-state value of the segregation index of the bi-disperse system. Time = 5 min is taken as a reference case while calculating change in SI. Table 2 shows he deviation of SI at different time values. To be on the safe side, a time value of 10 min is chosen so that there is no sensitivity of segregation with respect to time. From Fig. 6, a time value of 10 min is used as the base case for rotation time for entire work.

3.1.3. Effect of added energy

To examine the effect of added energy, the drum's rotational speed is increased. The rotational speed is donated by RPM and the unit of omega is RPM (rotation per minute). The RPM of the rotating drum can be varied from the variable frequency drive (VFD). The base case of coarse prolate and fine spheres are subjected to mixing in a rotating drum with varying speed of rotation.

Froude number is defined as the ratio of centrifugal force to gravitational force.

$$Froude\ number = \frac{rotational\ speed^{\ 2} \cdot drum\ inner\ radius}{gravitational\ constant} \tag{3}$$

With drum radius of 0.145 m, a filling height of 60%, and a rotational speed of 5 RPM, the Froude number is 4.05 E^{-04}, which falls in the rolling regime [43].

Fig. 7 shows plot of normalised fine mass fraction against the normalised radius for five different Ω. At 2 Ω the value of SI is 0.61. Increasing the RPM increases the rotational kinetic energy of the system. The particles use this energy to rearrange themselves from the initially separated state to the final mixed state. Result shows there is no significant change in segregation index by increasing the value of RPM from 4 to 20. The value of SI increases marginally. Therefore the value of 5 RPM is chosen as the base case. This result proves that mixing characteristics as measured by segregation index is independent of energy added to the system above a critical threshold (4 RPM in our study).

3.1.4. Effect of initial configuration of particle

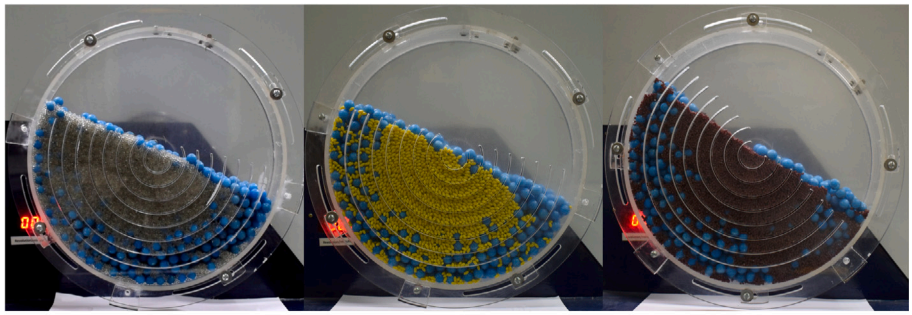
To examine the effect of the initial configuration/loading, the position of coarse and fine particles are interchanged in the bed. In the prior cases, the coarse particles are placed on top of the smaller particles (top-bottom loading), which is now replaced by a different configuration in which fine particles are placed over coarse particles (bottom-top loading). Table 3 shows the deviation of SI at different particle configuration. Coarse above fine configuration is taken as a reference while calculating % error. When the coarse particle is above the fine particle, the SI = 0.534; when the fine particles are above the coarse particle, the SI = 0.529. There is no significant difference (less than 1%) in the segregation index. Fig. 8 compares results of both configurations. The result indicates that the initial configuration of the system does not influence mixing.

Based on the of results of above study, the base case is chosen in which, coarse particles are placed over fine particles during the filling process. The drum is rotated for 10 min in which rotational speed is fixed at 5 RPM. During sampling, the section width is set at 15 mm.

3.2. Effect of coarse particle's shape

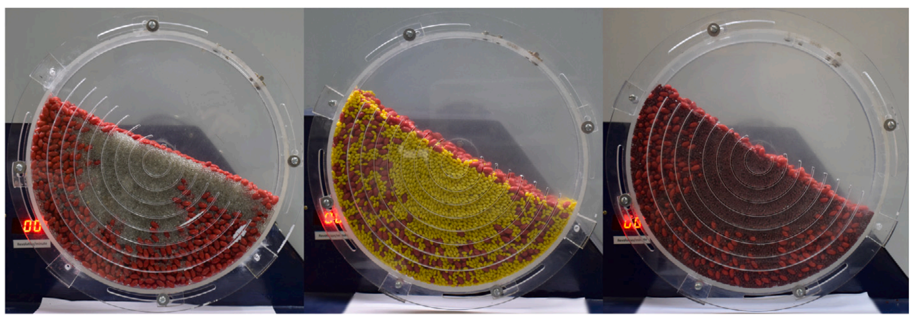
To examine the effect of coarse particle shape in different binary mixtures, the shape of coarse particles has been varied, while the shape of fine particles is kept fixed to a sphere or a prolate. There are four different shapes of coarse particles: sphere, elongated-needle, oblate, and prolate. Fig. 9 represents the actual images of a bi-disperse system of different coarse particles with fixed fine particles. Fig. 9(a) portrays the configuration when fine particle's shape is kept fixed to the prolate and Fig. 9(b) portrays the images when the fine particle's shape is fixed to the sphere.

The plot of normalised mass fraction fine (x_i/x_o) against normalised radius (r/R) is shown in Fig. 10. The effect of shape of coarse particle shows the decreasing trend of the SI as sphere (0.57) > oblate (0.53) > prolate (0.51) > elongated-needle (0.37). Fig. 10 indicates that best mixing is achieved in a mixture of coarse elongated needles with fine prolate particles, whereas the coarse sphere with fine prolate particles shows poor mixing. A similar trend is observed with a fine sphere in Fig. 11. The observed trend can be correlated to the packing density of mono-disperse coarse particles. The packing fraction of ellipsoids is less than spherocylinder (elongated-needle in our study) as reported by Li et al. [44]. Baule et al. [45] found that the value of packing density of spherocylinder (elongated-needle in our case) is 0.72. The value of packing density of oblate particles, suggested by Baule et al. [46] is 0.69, whereas Donev et al. [47] calculated packing density for prolate particles as 0.71. Jodrey et al. [48] and Li et al. [44], suggest value of packing density for the sphere is 0.64. Thus, the mono-disperse packing



Fine sphere Fine prolate Fine cube

(a) Coarse sphere with different fine particles.



Fine sphere Fine prolate Fine cube

(b) Coarse prolate with different fine particles.

Fig. 13. Actual image of bi-disperse system with different fine particles.

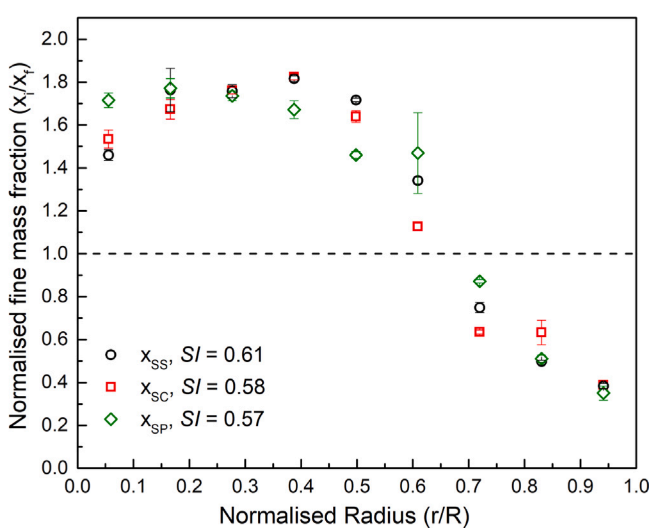


Fig. 14. Plot of normalised fine mass fraction versus normalised radius for different fine particles with fixed coarse sphere. Process parameter = Initially coarse sphere are placed over fine particles, time of revolution = 10 min and rotational speed = 5 RPM.

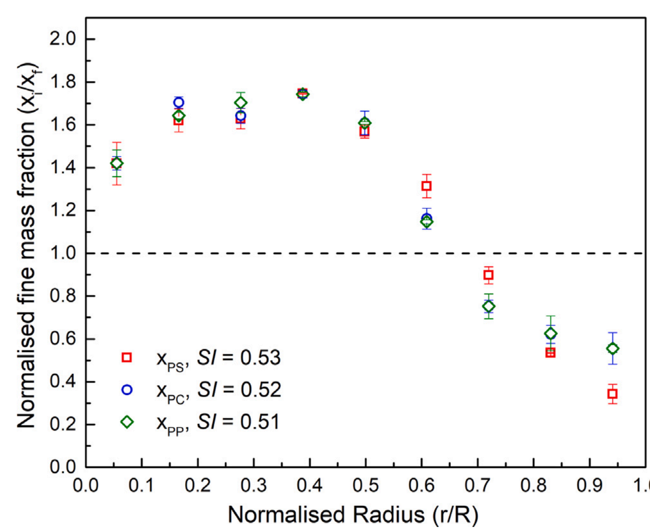


Fig. 15. Plot of normalised fine mass fraction versus normalised radius for different fine particles with fixed coarse prolate. Process parameter = Initially coarse prolate are placed over fine particle, time of revolution = 10 min and rotational speed = 5 RPM.

density follows the trend as sphere (0.64) < oblate (0.69) < prolate (0.71) < elongated-needle (0.72).

These trend are explained using the segregation index-packing density correlation. The voids of bulk mixture changes with the coarse particle shape. Different shapes correspond to different void spaces depending on the mono-disperse packing density. Higher the packing density lower is the size of available void spaces. The packing density thus has a significant impact on particle interaction and particle mobility (percolation) through these voids. Since spherical particles have the largest voids among other coarse particles, fine particles percolate through the coarse spheres easily; hence maximum segregation is observed.

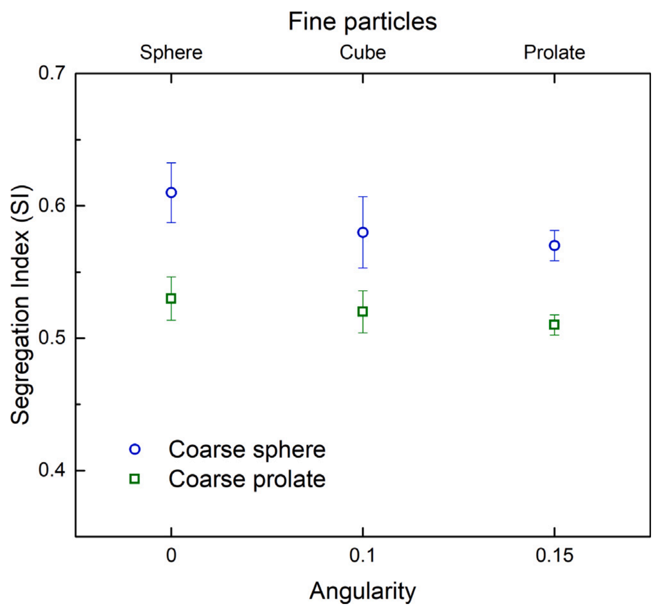


Fig. 16. Plot of segregation index for different fine particle's shapes.

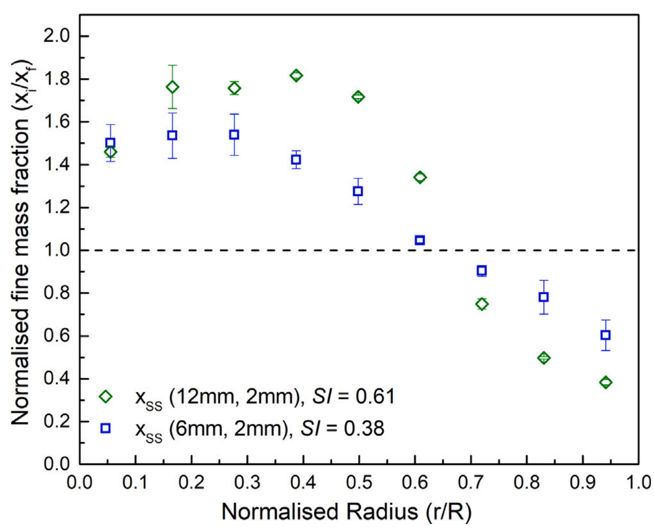


Fig. 17. Plot of normalised fine mass fraction versus normalised radius for different size of coarse particles with fixed fine particles. Process parameter = Initially coarse sphere are placed over fine sphere, time of revolution = 10 min and rotational speed = 5 RPM.

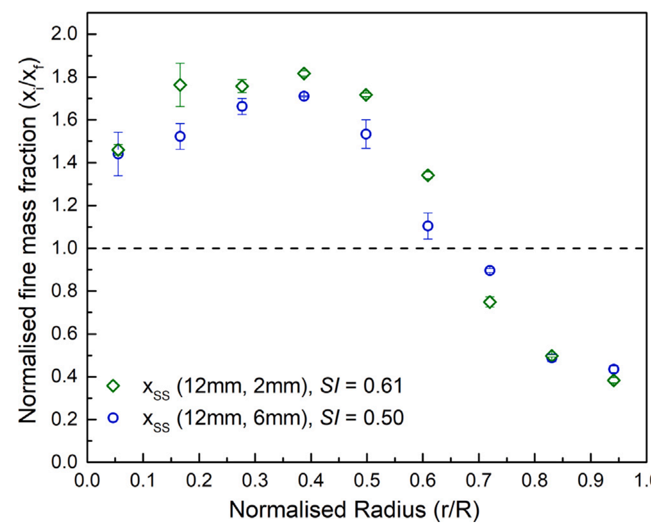


Fig. 18. Plot of normalised fine mass fraction versus normalised radius for different size of fine particles with fixed coarse particles. Process parameter = Initially coarse sphere are placed over fine sphere, time of revolution = 10 min and rotational speed = 5 RPM.

Fig. 12 shows a comparison of segregation indices for various shapes of coarse particles. A significant observation is that coarse elongated-needle shows better mixing compared to coarse spherical particles in a rotating drum. Ellipsoid particles show intermediate mixing among other non-spherical shapes. An important heuristic that can be derived from this work is that non-sphericity promotes mixing.

It is also important to notice that streaks and cores form in this section. Khakhar et al. [49] found that radial streaks are formed when particles are rotating at low rotational speeds with filling heights greater than half-filled cylinders, and according to Pereira et al. [50], the formation of radial streaks occurs in a thin drum with a high radius to length ratio. Our study satisfies both conditions; therefore, radial streaks can be seen in Fig. 9 when the coarse particle is the elongated needle. Aspect ratio is defined as the ratio of major axis to minor axis and is the controlling parameter in the streak formation. Aspect ratio of oblate, sphere, prolate and elongated needle are 0.5, 1, 2 and 6 respectively in this work. Based on the snapshots, the larger aspect ratio of coarse particles is associated with radial streaks. The longer and elongated part of the particle aligns toward the centre and forms streaks. Whereas in contrast, circular cores are formed when the aspect ratio is closer to 1.

3.3. Effect of fine particle's shape

To examine the effect of fine particle shape, the shape of a coarse particle is fixed in a mixture while the shape of fine particles varies. Three distinct shapes of fine particles used are prolate, sphere and cube. The shape of coarse particle is fixed to either a prolate or a sphere. Fig. 13 represent an actual image of a bi-disperse system with different fine particles while the shape of coarse particles is fixed. Fig. 13(a) portray bi-disperse mixtures where the coarse particles are fixed to a sphere whereas Fig. 13(b) portray a bi-disperse system where the shape of coarse particles is fixed to a prolate.

The trend of the normalised mass fraction of fine particles against normalised radius is plotted in Fig. 14. Fine particles with coarse sphere show the trend of the SI as sphere (0.61) > cubic (0.58) > prolate (0.57). The findings indicate that spherical particles have the most segregation while prolate particles have the least. Additionally, Fig. 15 shows the findings when the shape of a coarse particle is fixed as prolate instead of sphere. Similar trend of SI is obtained in this case i.e Sphere (0.53) > cube (0.52) > prolate (0.51).

The effect of fine particle shape can be correlated to the angularity of the particle. As the particle's shape changes from spherical to prolate, its angularity (sphericity of particle to number of vertices) increases. The theoretical value of angularity for the fine particle follows trend as, prolate (0.15) > cube (0.10) > sphere (0). The angularity-segregation correlation indicates that with increase in angularity, SI decreases. The voids formed by coarse particles remains the same in the bulk mixture. With increase in angularity, the mobility of the fine particles hindered due to the interlocking between particles. This phenomenon prevents the migration of fine particles towards the inner core of the drum, which reduces segregation. An important implication of this result is that fine non-spherical particles mix better in a rotating drum when compared with fine spherical particles(see Fig. 16).

Table 3
The deviation of SI at different particle configuration.

Configuration	SI	% Change in SI $= \frac{\lvert SI_{Coarseabovefine} - SI_x \rvert}{Maximum(SI_{Coarseabovefine}, SI_x)}$
Coarse particle above the fine particle	0.534	Reference
Fine particles above the coarse particle	0.529	0.93%

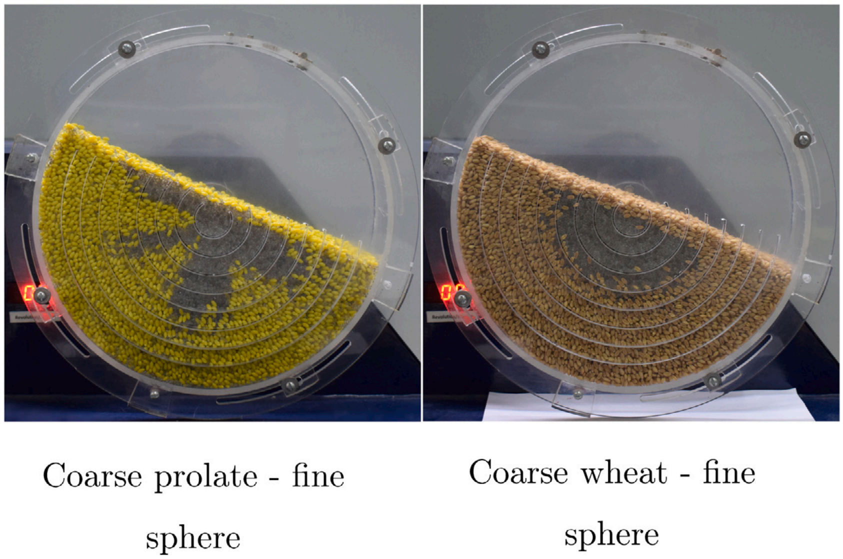


Fig. 19. Actual image of bi-disperse system with different coarse particles.

3.4. Effect of particle size ratio

To examine the effect of particle size ratio on segregation a spherical mixture (binary) is used as a base case. We categorise the experiments into two cases. In the first case, the size of coarse particles is reduced from 12 mm to 6 mm while the size of fine particles is kept constant at 2 mm. In the second case, the size of fine particles is increased from 2 mm to 6 mm while the size of coarse particles is kept constant at 12 mm. These comparisons are plotted in Figs. 17 and 18.

A size ratio in bi-disperse system of particle is the ratio of size of coarse particle divided by size of fine particles. Difference in particle size causes particles to flow from the active region to the drum's centre. Smaller particles settle near the drum's core, while the concentration of larger particles rises around the drum's periphery. Previous results show the similar outcome in a rotating drum [13,51,52]. This is a well-known result that can be explained with the help of the void structure of coarse particles and the mobility of fine particles.

In the first case, by decreasing the size of coarse particles from 12 mm to 6 mm, the value of the segregation index decreases. 12 mm particles form larger voids compared with 6 mm particles, in which 2 mm fine particles find it relatively easy to percolate through these larger voids, which implies that larger voids between coarse particles promote segregation. Similarly, In the second case, increasing the size of fine particles from 2 mm to 6 mm, the segregation index decreases. The 12 mm coarse particle leads to the same void structure. The 2 mm particles find it easy to move through and percolate through these voids as compared to the 6 mm particles, which is the cause of mixing in this case. This implies, as the size ratio of particles decreases, segregation decreases. This result shows good agreement with experimental and simulated results obtained in bi-disperse particle mixtures in a vibrating bed, rotating drum, and fluidised bed [49,53–57].

3.5. Effect of particle density

To examine the effect of particle density, two different coarse particles are used; one is engineered prolate, and the other is naturally occurring wheat. The shape and size of the wheat are identical to the engineered prolate particles. Engineered prolate particles are made of glass with a density of 2500 kg/m^3 while the density of wheat is 1250 kg/m^3. Both the particles are combined with fine spherical particles having 2 mm in size. Xu et al. [8] and Santos et al. [13], in their study found that the effect of density is significant as compared to frictional properties of particles. As a result, we assume that the change in segregation behaviour is primarily attributable to density differences and the effect of surface roughness is neglected. The assumption here is that the only important aspect is the difference in densities between the two prolate particles.

Fig. 19 shows the actual image of bi-disperse system with different densities. The result shows that the denser (thus more inertial) particles are concentrated near the core of the drum. The mixture with similar density, i.e., both coarse and fine, showed better mixing whereas the mixture with different densities (wheat as a coarser particle having less density) showed poor mixing (see Fig. 20).

This result can be explained with the help of stiffness of the voids in the bulk mixture. Engineered prolate has higher inertia due to high density therefore the voids formed by engineered prolate particles are more stiff compared to less inertial wheat particles. Fine particles find it easy to pass through less inertial wheat particles as the voids of wheat can expand locally, which is the cause of segregation in this case. This phenomena causes less-dense particles to settle away from the central axis and denser particles to settle near the central axis or core in a mobile bed. Similar results have been obtained by Metcalfe et al. [58], Pereira et al. [59] and Ristow et al. [60]

3.6. Effect of initial proportion of fines

In the studies conducted in the prior sections, the system is equipped with an equal weight of coarse and fine particles in every mixture. In this particular study, experiments are perform by varying amounts of fines in the mixture. Mass fraction of fines is decreased from 50% to 30%. A 30% system has 30% fines by weight. Results indicate that when the initial fines mass fraction of fines in mixture is reduced, the

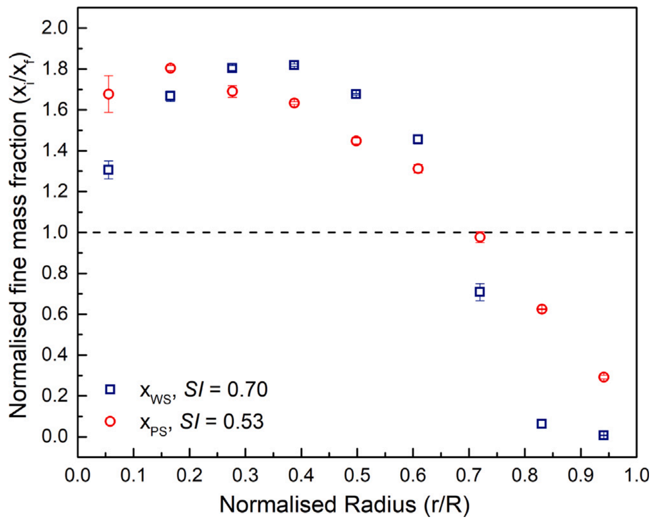


Fig. 20. Plot of normalised fine mass fraction versus normalised radius for coarse particles with different densities with fixed fine sphere. Process parameter = Initially coarse particle are placed over fine sphere, time of revolution = 10 min and rotational speed = 5 RPM.

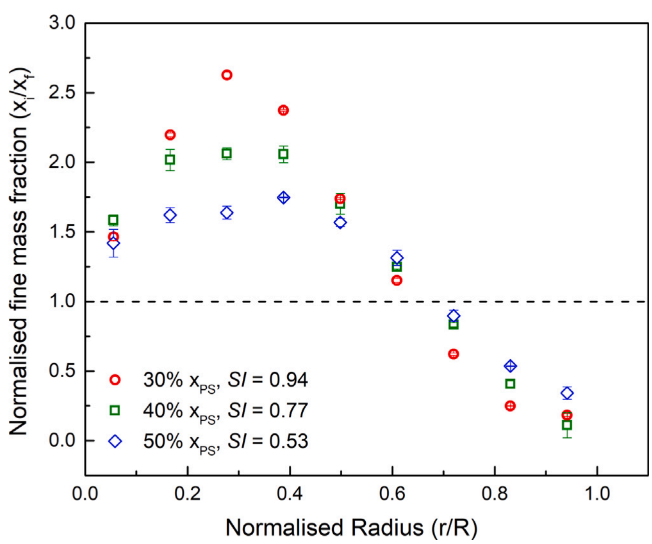


Fig. 21. Plot of normalised fine mass fraction versus normalised radius for different concentrations of fine particles by weight. Process parameter = Initially coarse prolate are placed over fine sphere, time of revolution = 10 min and rotational speed = 5 RPM.

segregation value increases. This can be seen in Fig. 21 as the value of segregation increases from 0.40 (50% fines) to 0.94 (30% fines).

This result can be explained with the help of the relative voids between coarse particles available for movement of fine particles. The size of the voids of the coarse particles remains unchanged however the number of fine particles per void space reduces as mass fraction of fine is reduced. This makes the percolation of fines easier as their concentration in the system reduces leading to more segregation.

4. Conclusions

The effect of various system and particle parameters on mixing of a bi-disperse mixture is studied in a rotating drum. Time sensitivity study suggests that the rotating drum reaches steady state value at time near 5 min whereas system parameter study indicates that the rotating drum is independent of the initial configuration of particles. Particle size and density are important parameters that play a prominent role to trigger segregation in a system. Particle shape plays a significant role in segregation of particles in a rotating drum. For the coarse particles, the decreasing trend for segregation is sphere > oblate > prolate > elongated-needle. The extent of segregation in a bi-disperse mixture is explained in terms of voids in coarse particles and relative mobility of fine particles. The correlation between the segregation index and mono-disperse packing fraction of particle suggest that increasing the mono-disperse packing fraction of coarse particles decreases the segregation in the system. For fine particles, the extent of segregation is high in the case of sphere as compared to cube and prolate particles. The correlation between segregation and angularity of fine particles suggests that in a bi-disperse mixture, fine particles with larger angularity aid in decreasing segregation. The size ratio study shows, as the size ratio of particles increases, the extent of segregation increases. Similarly, particle density study shows that the closer the density among binary particles, lower the segregation. The initial proportion of fines in bulk mixture also influences mixing and can be enhanced by increasing the proportion of fines in bulk mixture. In the future, more non-spherical particles will be considered along with particle image velocimetry (PIV) study to obtain intrinsic data on granular dynamics.

CRediT authorship contribution statement

Sunil Kumar: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing – original draft. **Salma Khatoon:** Visualization, Formal analysis. **Jeetram Yogi:** Visualization. **Sanjay Kumar Verma:** Visualization. **Anshu Anand:** Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Compliance with ethical standards

The authors declare that they have no conflict of interest.

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