Supplementary material

Study of the biomass, sand, and biochar fluidization in a typical bed of fast pyrolysis - statistical analysis

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S1.0 Segregation behavior

To compare the different measures of segregation percentage, we used the analysis of variance (ANOVA) (Palkar and Shilapuram, 2017; Yusup et al., 2014). ANOVA allows the significance of all main factors and their interactions to be evaluated by comparing the mean squares against an estimate of the experimental error at a specified confidence level. Table S1 shows the degrees of freedom, the sum-of-squares, the contribution of each parameter in the prediction model, the modified sum of the squares, the modified average sum of the squares, and the P-value for each studied fluidization parameter. Alpha was set at 0.1 (confidence level of 90%). Curvature was found nonsignificant, and therefore the linear model gave a better fit for the segregation percentage.

Table S1. ANOVA results of segregation percentage for the linear model.

	All variables				Significant variables			
	(SS)	(df)	(MS)	P	(SS)	(df)	(MS)	P
Curvature	41.621	1	41.621	0.142115				
d_{sand}	367.353	1	367.353	0.019724	367.353	1	367.353	0.019724
d_{bio}	210.666	1	210.666	0.033660	210.666	1	210.666	0.033660
w_{bio}	521.508	1	521.508	0.014016	521.508	1	521.508	0.014016
w_{bchar}	3.765	1	3.765	0.551259				
d_{sand}-d_{bio}	23.641	1	23.641	0.217129				
d_{sand}-w_{bio}	40.185	1	40.185	0.146134				
d_{sand}-w_{bchar}	250.100	1	250.100	0.028578	250.100	1	250.100	0.028578
d_{bio}-w_{bio}	343.533	1	343.533	0.021049	343.533	1	343.533	0.021049
d_{bio}-w_{bchar}	45.777	1	45.777	0.131645				
w_{bio}-w_{bchar}	22.709	1	22.709	0.223274				
d_{sand}-d_{bio}-w_{bio}	3.520	1	3.520	0.563235				
d_{sand}-d_{bio}-w_{bchar}	596.207	1	596.207	0.012292	596.207	1	596.207	0.012292
d_{sand}-w_{bio}-w_{bchar}	382.142	1	382.142	0.018983	382.142	1	382.142	0.018983
d_{bio}-w_{bio}-w_{bchar}	5.313	1	5.313	0.487704				
Lack of Fit	208.755	1	208.755	0.33953	395.285	9	43.9205	0.153678

Pure Error	14.932	2	7.4659	14.932	2	7.4659
Total SS	3081.726	18		3081.726	18	
R^2	0.93			0.87		
R^2 adj	0.56			0.78		

The main variable (w_{bchar}), the first-order interactions (d_{sand}-d_{bio}, d_{sand}-w_{bio}, d_{bio}-w_{bchar}, w_{bio}-w_{bchar}), and second-order interaction (d_{sand}-d_{bio}-w_{bchar}, d_{bio}-w_{bio}-w_{bchar}) were found to be nonsignificant, and were removed from the calculation. The other response variables had P-values below 0.1. The coefficient of determination (R^2) shows how well a change in response was explained by the model. The model better predicted the segregation percentage when R^2 was close to unity, as shown in Table 5 (0.93). R^2 was adjusted (R^2 adj) to take account of the number of predictors in the model, allowing models with different numbers of predictors to be compared. Table S1 shows that R^2 adj = 0.56 when all test variables were considered. However, the adjusted R^2 remained closer to R^2 when the nonsignificant variables were removed from the model (R^2 adj = 0.78), suggesting that it was a better predictor of segregation percentage. Pure-error and lack-of-fit are taken account of in the residual sums of squares when testing a hypothesis. The pure-error cannot be predicted by including additional terms, whereas lack-of-fit can be predicted by including additional terms for the predictor variables. Table S1 shows a non-significant P-value (> 0.1) for lack-of-fit. A test of lack-of-fit for the model without the additional terms was performed using the mean square pure error as the error term. We determined a mean square pure error of 7.4659, which suggests that the calculated model values had medium variability around the mean.

Measures of adjustment quality were used to assess the divergence between the observed values and the values predicted by the model. According to the calculated statistical parameters, the sensitivity analysis is sufficiently accurate. The final model used to assess the segregation percentage was the first-order polynomial regression model (Eq. (S1)):

$$S = 10.203 + 5.792\, d_{sand} - 3.629\, d_{bio} + 5.709\, w_{bio} - 3.954\, d_{sand}\, w_{bchar} - 4.634\, d_{bio}\, w_{bio} + 6.001\, d_{sand}\, d_{bio}\, w_{bchar} - 4.987\, d_{sand}\, w_{bio}\, w_{bchar} \qquad \text{(S1)}$$

The model was verified using experimental data. Fig. S1 compares the measured segregation percentage values with the values calculated using Eq. (S1). Table 2 shows the experimental segregation percentage data used for model verification, as well as the independent variable coded data used to predict the segregation percentage. The results were sufficiently close to confirm the predictive accuracy of the model.

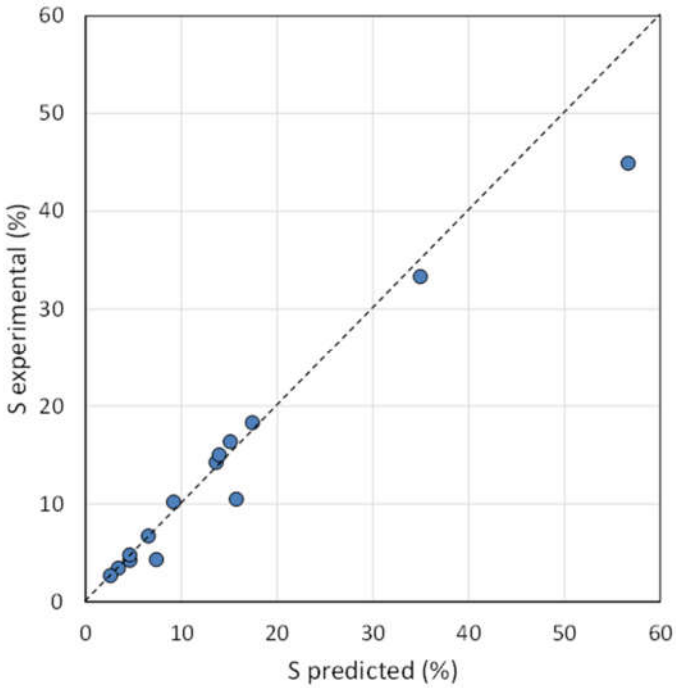

Fig. S1. Experimental end predicted segregation percentage.

From Eq. (S1) the terms that most influenced the S value were dsand, wbio, and the interaction between d_{sand}, $d_{bio,}$ and w_{bchar}. These three terms caused increases in S, though the term d_{bio} and interactions d_{sand}-w_{bchar}, d_{bio}-w_{bio} and d_{sand}-w_{bio}-w_{bchar} have antagonistic effects on S. The effects of the main variables d_{sand}, d_{bio} and w_{bio} are well recognized in the literature (Cluet et al., 2015; Shao et al., 2016). However, the variation of S caused by the synergy between d_{sand}, d_{bio}, $w_{bio,}$ and w_{bchar} is a novel aspect that arose in this work.

S2.0 U_{ff} behavior

To evaluated the different measures of segregation percentage between them, the analysis of variance (ANOVA) was also used (Table S2). The main variable (w_{bchar}) and the first-order interactions, (d_{sand}-d_{bio}, d_{sand}-w_{bio}, w_{bio}-w_{bchar}) were nonsignificant, and were removed from the calculation. The other response variables had P-values below 0.1. In order to obtain a model that better predicted the final fluidization velocity, R^2 should be close to unity. From Table S2, it can be observed that when all the variables are considered, R^2 is 0.90, but the adjusted R^2 is 0.77. However, when the nonsignificant variables were removed from the model, the adjusted R^2 (0.81) gets closer to R^2 (0.89), suggesting that it was a better predictor of final fluidization velocity. Table S2 shows a non-significant P-value (> 0.1) for lack-of-fit. Mean square pure error of 0.000867 suggests that the calculated model values had low variability around the mean.

Table S2. ANOVA results of final fluidization velocity for the quadratic model.

	All variables				Significant variables			
	(SS)	(df)	(MS)	P	(SS)	(df)	(MS)	P
d_{sand}	0.088573	1	0.088573	0.009647	0.088573	1	0.088573	0.009647
d_{bio}	0.017822	1	0.017822	0.045364	0.017822	1	0.017822	0.045364
w_{bio}	0.026934	1	0.026934	0.030714	0.026934	1	0.026934	0.030714
w_{bchar}	0.000938	1	0.000938	0.407610				
d_{sand}^2	0.013445	1	0.013445	0.058851	0.013445	1	0.013445	0.058851
d_{bio}^2	0.030368	1	0.030368	0.027383	0.030368	1	0.030368	0.027383
w_{bio}^2	0.007584	1	0.007584	0.097836	0.007584	1	0.007584	0.097836
w_{bchar}^2	0.007584	1	0.007584	0.097836	0.007584	1	0.007584	0.097836
d_{sand} by d_{bio}	0.000600	1	0.000600	0.492901				
d_{sand} by w_{bio}	0.007832	1	0.007832	0.095159				
d_{sand} by w_{bchar}	0.010201	1	0.010201	0.075493	0.010201	1	0.010201	0.075493
d_{bio} by w_{bio}	0.003969	1	0.003969	0,165764	0.003969	1	0.003969	0.165764
d_{bio} by w_{bchar}	0.000600	1	0.000600	0.492901	0.007832	1	0.007832	0.095159
w_{bio} by w_{bchar}	0.000156	1	0.000156	0.712492				
Lack of Fit	0.020568	10	0.002057	0.332822	0.022862	14	0.001633	0.400552
Pure Error	0.001734	2	0.000867		0.001734	2	0.000867	
Total SS	0.214484	26			0.214484	26		
R^2	0.90				0.89			
R^2 adj	0.77				0.81			

Measures of adjustment quality were also used to assess the divergence between the observed values and the values predicted by the model. The final model used to assess the final fluidization velocity was the second-order polynomial regression model (Eq. (S2)):

$$U_{ff} = 0.470 + 0.061\ d_{sand} + 0.027\ d_{bio} + 0.033\ w_{bio} - 0.025\ d_{sand}\ w_{bchar} + 0.016\ d_{bio}\ w_{bio} - 0.022\ d_{sand}\ w_{bio} + 0.025\ d^2_{sand} + 0.038\ d^2_{bio} + 0.019\ w^2_{bio} + 0.019\ w^2_{bchar} \quad (S2)$$

Fig. S2 compares the measured final fluidization velocity values with the values calculated by Eq. (S2). Table 2 shows the experimental final fluidization velocity data used for model verification, as well as the independent variable coded data used to predict the final fluidization velocity. The results were sufficiently close to confirm the predictive accuracy of the model.

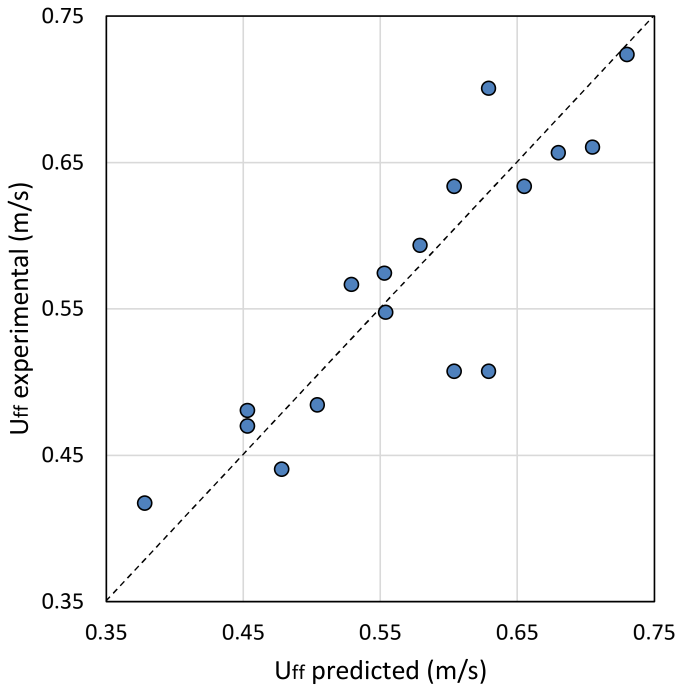

Fig. S2. Experimental end predicted segregation percentage.

From Eq. (S2), the term d_{sand} and d_{bio}^2 were the ones that most influenced the final fluidization velocity, while d_{bio} was the least sensitive. Most of the terms increased the final fluidization velocity. However, the interactions d_{sand}-w_{bchar} and d_{sand}-w_{bio} have the opposite effect. The effects of the main variables d_{sand}, d_{bio} and w_{bio} are well recognized in the literature (Vasconcelos et al., 2018). Nevertheless, the variation of final fluidization velocity caused by the synergy between d_{sand}, d_{bio}, $w_{bio,}$ and w_{bchar} is a novel aspect that arose in this work.

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