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Article

Removal Effectiveness of Nanoplastics (<400 nm) with Separation Processes Used for Water and Wastewater Treatment

Audrey Murray and Banu Örmeci *

S1: Factorial Experiment for Ballast Flocculation (data)

Since there were many factors (alum dose, polymer dose, the percent of the polymer added initially, sand dose, mixing intensity, coagulation time, flocculation time, and settling time) capable of influencing the effectiveness of the ballasted flocculation treatment, a statistical approach employing a 2^{8-4} factorial design was used to determine which factors had a significant impact on performance. A linear regression model was obtained from the results.

The 2^{8-4} factorial design varied alum dose, polymer dose, percent of polymer added initially, sand dose, mixing intensity, coagulation time, flocculation time, and settling time between two different conditions (identified as 1 and −1 in Table S1-1, below). Decoded values are shown in Table S1-2.

Table S1–1. 2^{8-4} factorial design conditions for ballasted flocculation removal of nanoplastic particles.

alum dose	polymer dose	Percent of polymer added initially	sand dose	mixing intensity	coagulation time	flocculation time	settling time
1	1	−1	1	−1	−1	−1	1
−1	1	−1	1	−1	1	1	−1
1	−1	−1	1	1	−1	1	−1
−1	−1	−1	1	1	1	−1	1
1	1	1	1	1	1	1	1
−1	1	1	1	1	−1	−1	−1
1	−1	1	1	−1	1	−1	−1
−1	−1	1	1	−1	−1	1	1
1	1	−1	−1	1	1	−1	−1
−1	1	−1	−1	1	−1	1	1
1	−1	−1	−1	−1	1	1	1
−1	−1	−1	−1	−1	−1	−1	−1
1	1	1	−1	−1	−1	1	−1
−1	1	1	−1	−1	1	−1	1
1	−1	1	−1	1	−1	−1	1
−1	−1	1	−1	1	1	1	−1

Table S1-2. 2^{8-4} factorial design results and decoded design parameters for ballasted flocculation removal of nanoplastic particles.

alum dose (mg/L)	polymer dose (µg/L)	polymer percent added initially (%)	sand dose (g/L)	mixing intensity (rpm)	coagulation time (min)	flocculation time (min)	settling time (min)	average turbidity (NTU)	standard deviation turbidity (NTU)	Average pH	standard deviation pH
5	0.2	70	2	300	4	10	3	2.87	0.10	7.04	0.07
10	0.2	30	2	150	4	6	6	1.26	0.05	6.89	0.03
10	1.0	30	4	150	2	6	6	2.40	0.61	6.83	0.11
5	0.2	30	2	150	2	10	3	3.98	0.71	7.07	0.03
10	1.0	30	2	300	4	6	3	1.31	0.40	7.05	0.02
10	1.0	70	2	150	2	10	3	2.00	0.47	7.09	0.03
5	1.0	70	2	150	4	6	6	3.88	0.45	7.17	0.02
10	1.0	70	4	300	4	6	6	1.39	0.39	7.12	0.03
10	0.2	30	4	300	2	6	3	1.28	0.25	7.09	0.03
5	0.2	70	2	150	2	10	6	5.68	0.82	7.21	0.01
10	0.2	70	2	300	2	6	6	1.04	0.24	7.11	0.04
5	1.0	30	2	300	2	10	6	3.32	0.59	7.13	0.02
5	1.0	30	4	150	4	10	3	2.95	0.23	7.16	0.03
5	1.0	70	4	300	2	10	3	3.82	1.25	7.22	0.02
10	0.2	70	4	150	4	6	3	1.62	0.61	7.10	0.02
5	0.2	30	4	300	4	10	6	1.49	0.27	7.21	0.02

A preliminary ANOVA analysis, completed in Excel, indicated that the alum dose, mixing intensity, and coagulation time were significant. Table S1-3, below, provides the results of the ANOVA analysis.

Table S1-3. ANOVA analysis of significant factors.

Multiple R	**0.935094898**					
R Square	0.874402468					
Adjusted R Square	0.730862432					
Standard Error	0.693583572					
Observations	16					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	8	23.44368655	2.930460819	6.091697416	0.013856122	
Residual	7	3.367407199	0.481058171			
Total	15	26.81109375				
	Coefficients	*Standard Error*	*t Stat*	*P−value*	*Lower 95%*	*Upper 95%*
Intercept	9.546446596	2.730699408	3.495971241	0.01004744	3.089368555	16.00352464
X Variable 1	−0.472420188	0.116117095	−4.068480943	0.004758343	−0.746993486	−0.197846889
X Variable 2	0.03220804	0.043728901	0.736538968	0.485348816	−0.071194381	0.135610461
X Variable 3	0.012829225	0.00874578	1.466904603	0.185837239	−0.007851259	0.033509709
X Variable 4	−0.09899061	0.184057969	−0.537823006	0.607366327	−0.534218548	0.336237327
X Variable 5	−0.005887793	0.002332208	−2.524557518	0.039546218	−0.011402589	−0.000372998
X Variable 6	−0.480434272	0.190835364	−2.517532715	0.039954393	−0.931688202	−0.029180342
X Variable 7	−0.141866197	0.155362807	−0.913128435	0.391539467	−0.509240859	0.225508465
X Variable 8	−0.029565728	0.12796111	−0.231052447	0.823882156	−0.332145672	0.273014217

Because the results indicated that not all of the factors tested in Table S1-2 were significant, tests were repeated varying only alum dose, mixing intensity, and coagulation time, as shown below in Table S1-4.

Table S1-4. 2^{8-4} factorial design results and decoded design parameters for ballasted flocculation removal of nanoplastic particles, insignificant parameters removed.

alum dose (mg/L)	mixing intensity (rpm)	coagulation time (min)	average turbidity (NTU)
5	300	4	2.87
10	150	4	1.26
10	150	2	2.40
5	150	2	3.98
10	300	4	1.31
10	150	2	2.00
5	150	4	3.88
10	300	4	1.39
10	300	2	1.28
5	150	2	5.68
10	300	2	1.04
5	300	2	3.32
5	150	4	2.95
5	300	2	3.82
10	150	4	1.62
5	300	4	1.49

The resulting ANOVA results, shown in Table S1–5, below, indicated that alum dose, mixing intensity, and coagulation time were, in fact, significant, and were used to generate Equation (1), shown in the article.

Table S1-5. ANOVA analysis of significant factors for alum dose, mixing intensity, and coagulation time.

Regression Statistics						
Multiple R	0.338161					
R Square	0.114353					
Adjusted R Square	−0.10706					
Standard Error	1.406686					
Observations	16					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	3	3.065919	1.021973	0.51647	0.678739	
Residual	12	23.74518	1.978765			
Total	15	26.81109				
	Coefficients	*Standard Error*	*t Stat*	*P−value*	*Lower 95%*	*Upper 95%*
Intercept	2.519375	0.351671	7.164003	1.14E−05	1.753149	3.285601
X Variable 1	−0.34896	0.351671	−0.99229	0.340646	−1.11518	0.417268
X Variable 2	−0.04854	0.351671	−0.13803	0.892505	−0.81477	0.717685
X Variable 3	−0.25979	0.351671	−0.73873	0.47427	−1.02602	0.506435

S2: Steepest Ascent Optimization of Ballast Flocculation (data)

Using the equation determined from the factorial experiment, the steepest ascent method (or in this case descent) was used for optimization.

Table S2-1. Steepest ascent values used to optimized ballasted flocculation.

	Alum dose (mg/L)	**Speed (rpm)**	**Coagulation time (min)**
Design Center point	7.5	200	3
Value of one coded unit	2.5	50	1
Direction of steepest ascent (coded)	0.35	0.049	0.26
Value in the original units	0.875	2.45	0.26
Path	8.375,9.25,10.125, 11	202.45, 204.9, 207.35, 209.8	3.26, 3.52, 3.78, 4.04

Center point values were used for the parameters which were not found to be significant from the factorial experiment.

1. Sand dose: 3 g
2. Polymer dose: 6 mL
3. Percent of the polymer added in the first addition: 50%
4. Flocculation time: 8 minutes
5. Settling time: 4.5 minutes

Table S2-2. below, shows the results of the steepest ascent method used to determine the optimized conditions and removal. The steps are outlined in Table S2-1, above.

Table S2-2. Steepest ascent optimization of ballasted sand flocculation.

Step	Average Turbidity (NTU)	Standard Deviation Turbidity (NTU)	Percent Removal (%)
1	4.13	0.22	86.14
2	3.72	0.26	87.51
3	3.97	0.27	86.68