Electronic Supplementary Material (ESI) for Green Chemistry.

Supplementary information for:

More than a fertilizer: wastewater-derived struvite as a high value, sustainable fire retardant

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Appendix A

Methodology for Technoeconomic Analysis of Struvite-based Fire Retardant Production

A technoeconomic analysis (TEA) was performed to estimate costs of hydrogel production, as well as costs of incorporating dried struvite into hydrogels to create fire retardants. This TEA does not estimate capital and operational costs for struvite recovery at wastewater treatment plants, which has been reported elsewhere[1].

General Assumptions

To estimate the per kg P costs of producing struvite-based fire retardants, a 38,000 m^3/day (10 mgd) wastewater treatment plant was considered. For such a plant, we estimate the struvite-based fire retardant production to range from 488 to 3900 m^3/year depending on the phosphorus recovery rate and wastewater strength. Standard commercial fire retardants are stored, sold, and distributed as a concentrate that must be diluted by a factor of 6.5 on site before being aerial dropped. In order to be conservative with equipment sizing and cost demands, we assume struvite-based fire retardants will only be concentrated by a factor of 2 for handling at wastewater treatment plants. A summary of all TEA assumptions and results can be found in Table S3.

Capital Cost Assumptions

The annualized capital cost (USD/kg P) for hydrogel production, assuming yearly loan repayments for a period of 15 years, was calculated through the following equation:

$$Annualized\ Cost = \left(\frac{Rate}{1-(1+Rate)^{-Lifetime}}\right) * Unit\ Capital\ Cost$$

Where the interest rate was assumed to be 10%, the equipment lifetime was assumed to be 15 years, and the unit capital cost is reported in units (USD/kg P/year). To determine the capital investment of hydrogel production, we assumed the necessary equipment to include a storage tank, a mixing tank, an industrial mixer, and a ball mill for struvite grinding. We estimated volumetric capital costs for tanks and industrial mixers to be 342.50 USD/m^3 concentrate and 43.28 USD/m^3 concentrate, respectively, based on reported values from Verrecht et al. (2010), adjusted to 2019 prices to account for inflation. The storage tank volume was sized to contain one year's worth of produced fire retardant concentrate to correspond with peak demands during wildfire seasons. The volume of the mixing tank, which is used for combining struvite and other hydrogel components, was assumed to be a quarter of the storage tank size. We assumed the capital cost of a ball mill to be $21,250 for a mill with a 1 t/hr grinding capacity[3], which is far more than the expected struvite production rate for a 38,000 m^3/day treatment plant (< 0.03 t/hr struvite). To be conservative, we used the highest unit capital cost for the ball mill when considering the range of struvite-fire retardant production at a 38,000 m^3/day plant.

Chemical Cost Assumptions

Hydroxyethylcellulose (HEC), methylcellulose (MC), and colloidal silica nanoparticles (CSNP) are the only necessary chemicals for hydrogel production. We used average reported manufacturer prices for HEC, MC, and CSNP, summarized in Table S3.

Electricity Costs Assumptions

To estimate electricity usage for pumping and mixing of struvite-based fire retardant concentrates, we used a conservative rate of 1.5 kWh/m^3 based on values reported by Pikaar et al. (2018). To estimate electricity costs, we used a value of 0.106 USD/kWh based on the average 2019 electricity price[5]. We neglect electricity consumption demands of the ball mill in

this analysis, because mill usage would likely be scarce and intermittent based on the reported 1 t/hr grinding capacity.

Overhead Costs Assumptions

We assume overhead costs to account for labor, installation maintenance, quality testing, packaging, and other miscellaneous operational costs[4]. To be conservative, we assume an overhead cost equal to 100% of the total annualized capital cost[4].

Table S1. Literature values for reported and suggested struvite sales prices. Values are adjusted and reported as average 2019 USD prices to account for inflation.

Reference	Original Reported Price	Original Reported Unit	Adjusted 2019 Price (USD/ton)	Adjusted 2019 Price (USD/kg)	Adjusted 2019 Price (USD/kg P)
Bashar et al. (2018)	460	USD/ton	488	0.54	4.26
Booker (1999)	877	USD/t	1226	1.35	10.70
Dirk (2009)	320	€/ton	519	0.57	4.53
Dirk (2009)	1290	€/ton	2092	2.31	18.25
Dockhorn (2009)	760	€/ton	1232	1.36	10.75
Egle et al. (2016)	0.306	€/kg	327	0.36	2.85
Gadekar (2011)	500	USD/ton	576	0.63	5.02
Gaterell et al. (2000)	250	USD/t	342	0.38	2.98
Jaffer et al. (2001)	283	USD/t	375	0.41	3.27
Jia et al. (2017)	613	USD/ton	641	0.71	5.60
Khater et al. (2015)	2000	USD/ton	2121	2.34	18.51
Li et al. (2019)	740	USD/t	671	0.74	5.86
Münch and Barr (2000)	276	USD/t	378	0.42	3.30
Rein and Associates (2008)	1500	USD/ton	1817	2.00	15.86
Sampat et al. (2018)	0.8	USD/kg	744	0.82	6.49
Sena et al. (2020)	0.39	USD/kg (2017)	372	0.41	3.25
Shu et al. (2006)	464	€/ton	752	0.83	6.56

Sikosana et al. (2017)	6.6	R/kg	508	0.56	4.43
Stamatelatou & Konstantinos (2015)	234	USD/ton	248	0.27	2.17
Taruya (2000)	1885	USD/t	2579	2.84	22.51
Ueno & Fujii (2001)	27000	yen/t	327	0.36	2.85
Yetilmezsoy et al. (2017)	560	€/ton	662	0.73	5.78
Average			864	0.95	7.54
Standard Deviation			682	0.75	5.95
25th Percentile			375	0.41	3.28
Median			609	0.67	5.31
75th Percentile			1108	1.22	9.67

Table S2. Reported 2019 prices for Phos-Chek Fire Retardants. PC LC95 prices are originally reported in USD/ton concentrate or USD/gal concentrate. PC LC95 concentrates must be diluted by a factor of 6.5 before deployment as a fire retardant. Reported densities of PC LC95 products are 1467 kg/m^3 for concentrates and 1077 kg/m^3 after dilution.

Product Name	Product Size	Description	USD/ton conc.	USD/gal conc.	USD/kg conc.	USD/m^3 conc.	USD/ton fire retardant	USD/gal fire retardant	USD/kg fire retardant	USD/m^3 fire retardant
LC95A-R	Bulk Tanker	FOB Moreland, ID	2656.19	16.36	2.93	4321.65	560.04	2.52	0.62	664.87
LC95A-R	Bulk Tanker	FOB Buckeye, AZ	2954.36	18.20	3.26	4806.78	622.90	2.80	0.69	739.50
LC95A-R	Bulk Tanker	FOB Pasco, WA	2816.45	17.35	3.10	4582.40	593.83	2.67	0.65	704.98
LC95A-R	260 Gallon Tote	FOB Moreland, ID	2805.69	17.28	3.09	4564.89	591.56	2.66	0.65	702.29
LC95A-R	260 Gallon Tote	FOB Rancho Cucamonga, CA	3724.69	22.94	4.11	6060.11	785.32	3.53	0.87	932.32
LC95A-R	260 Gallon Tote	FOB Rancho Cucamonga, CA	4789.81	29.5	5.28	7793.07	1009.89	4.54	1.11	1198.93
LC95A-R	55 Gallon Drum	FOB Rancho Cucamonga, CA	3950.88	24.33	4.35	6427.30	832.91	3.74	0.92	988.82
LC95A-R	55 Gallon Drum	FOB Rancho Cucamonga, CA	5073.95	31.25	5.59	8255.38	1069.80	4.81	1.18	1270.06
LC95A-R	5 Gallon Pail	FOB Rancho Cucamonga, CA	5073.95	31.25	5.59	8255.38	1069.80	4.81	1.18	1270.06
LC95A-FX	Bulk Tanker	FOB Moreland, ID	2951.28	18.18	3.25	4801.77	622.25	2.80	0.69	738.73
LC95A-FX	Bulk Tanker	FOB Buckeye, AZ	3229.95	19.89	3.56	5255.16	681.01	3.06	0.75	808.49
LC95A-FX	Bulk Tanker	FOB Pasco, WA	3103.28	19.11	3.42	5049.07	654.30	2.94	0.72	776.78
LC95A-FX	260 Gallon Tote	FOB Moreland, ID	3190.50	19.65	3.52	5190.98	672.69	3.02	0.74	798.61
LC95A-FX	260 Gallon Tote	FOB Rancho Cucamonga, CA	4132.23	25.45	4.55	6723.18	871.25	3.92	0.96	1034.33
LC95A-FX	260 Gallon Tote	FOB Rancho Cucamonga, CA	4690.77	28.89	5.17	7631.93	989.01	4.44	1.09	1174.14
LC95A-FX	55 Gallon Drum	FOB Rancho Cucamonga, CA	4346.55	26.77	4.79	7071.88	916.44	4.12	1.01	1087.98
LC95A-FX	55 Gallon Drum	FOB Rancho Cucamonga, CA	5798.23	35.68	6.39	9425.66	1221.46	5.49	1.35	1450.10
LC95A-FX	5 Gallon Pail	FOB Rancho Cucamonga, CA	5643.86	34.76	6.22	9182.62	1189.96	5.35	1.31	1412.71
LC95W	260 Gallon Tote	FOB Moreland, ID	2805.69	17.28	3.09	4564.89	591.56	2.66	0.65	702.29
LC95W	260 Gallon Tote	FOB Rancho Cucamonga, CA	3724.69	22.94	4.11	6060.11	785.32	3.53	0.87	932.32

LC95W	260 Gallon Tote	FOB Rancho Cucamonga, CA	4789.81	29.5	5.28	7793.07	1009.89	4.54	1.11	1198.93
LC95W	55 Gallon Drum	FOB Rancho Cucamonga, CA	3950.38	24.33	4.35	6427.30	832.91	3.74	0.92	988.82
LC95W	55 Gallon Drum	FOB Rancho Cucamonga, CA	5073.95	31.25	5.59	8255.38	1069.80	4.81	1.18	1270.06
LC95W	5 Gallon Pail	FOB Rancho Cucamonga, CA	5073.95	31.25	5.59	8255.38	1069.80	4.81	1.18	1270.06
Wildfire Home Defense	0.75 Gallon Container	Perimeter Solutions	9737.66	59.97	10.73	15843.28	2001.78	9.00	2.21	2376.49
Wildfire Home Defense	0.75 Gallon Container	Amazon, Home Depot	6490.33	39.97	7.15	10559.84	1334.22	6.00	1.47	1583.98
		Average	4329.75	26.67	4.77	7044.56	909.60	4.09	1.00	1079.87
		Standard Deviation	1538.19	9.47	1.70	2502.65	315.27	1.42	0.35	374.28
		25^{th} Percentile	3125.09	19.25	3.44	5084.55	658.90	2.96	0.73	782.24
		Median	4041.30	24.89	4.45	6575.24	852.08	3.83	0.94	1011.58
		75^{th} Percentile	5073.95	31.25	5.59	8255.38	1069.80	4.81	1.18	1270.06

Supplementary material

Table S3. List of assumptions and results for technoeconomic analysis of struvite-based fire retardant production for a 38,000 m^3/d plant.

	Value	Unit	Annualized Cost (USD/kg P)	Reference
General Assumptions				
Concentration Factor	2			
Equipment Life	15	Years		
Payback Period	15	Years		
Interest Rate	10%	%		
Salvage Value	0	USD		
Capital Costs				
Tanks (Storage and Mixing)	342.50	USD/m^3	1.66	Verrecht et al. (2010)
Industrial Mixer	43.28	USD/m^3	0.17	Verrecht et al. (2010)
Ball Mill	21,250	USD/mill	0.04-0.33	Garrett (1989)
Total Capital Cost			2.16	
Chemical Costs				
Hydroxyethylcellulose	5	USD/kg	1.99	Xi'an Sheerherb Biological Technology Co., Ltd.
Methylcellulose	3.5	USD/kg	0.25	Shanghai Honest Chem. Co., Ltd.
Colloidal Silica Nanoparticles	0.6	USD/kg	1.76	Qingdao Hengze Silica Gel Products Co., Ltd.

Total Chemical Cost			4.00	
Electricity Costs				
Pumping and Mixing	0.16	USD/m^3	0.005	Pikaar et al. (2018)
Overhead Costs				
Rate of Overhead (Percentage of Total Capital Cost)	100%	%	2.16	Pikaar et al. (2018)
Total			8.32	

Fig S1

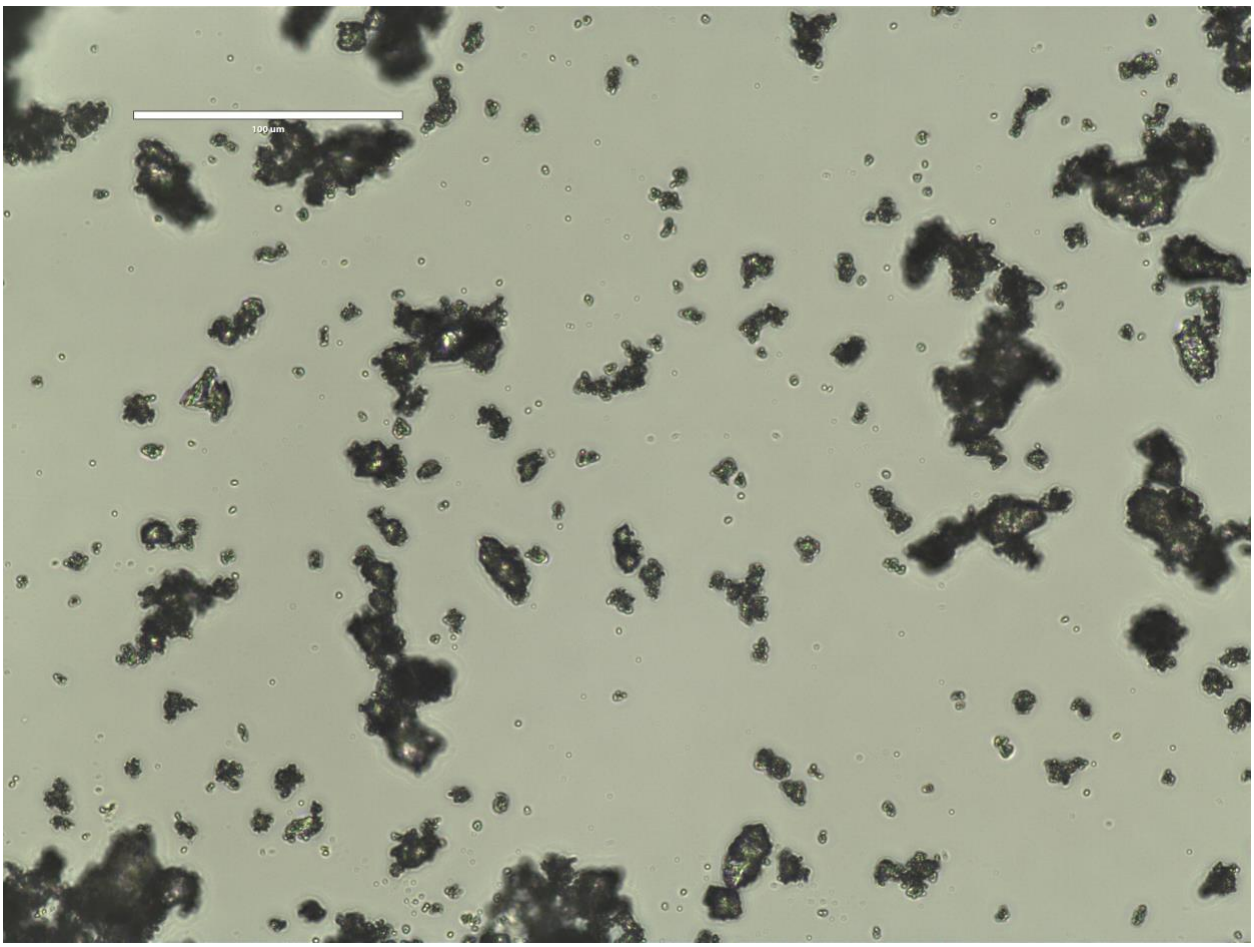

Fig S1. Image taken of the struvite crystals after grinding using an EVOS XL Core Imaging System microscope. A range of struvite particle size was obtained. The size of any individual struvite particle is less than 50 µm.

Fig S2

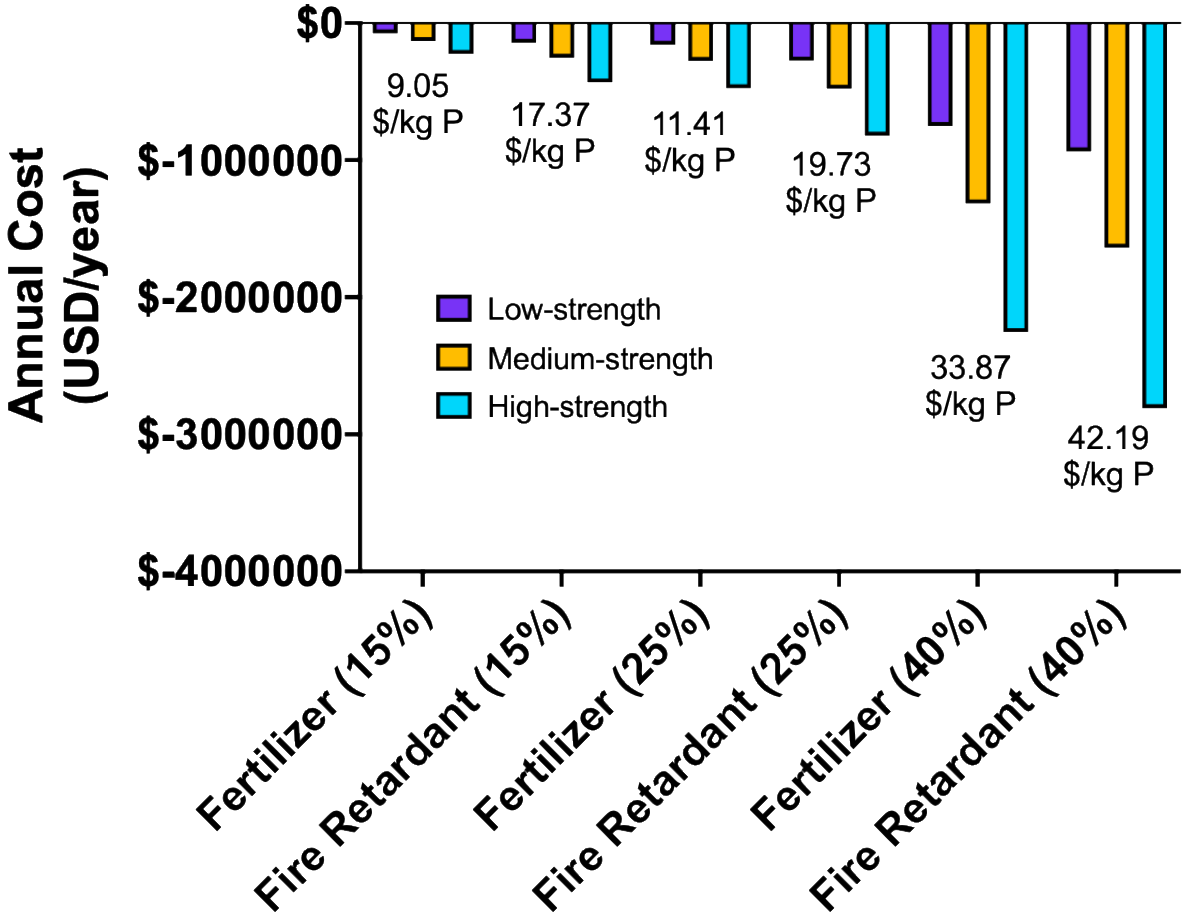

Fig S2. Estimated production costs for struvite fertilizer or struvite-based fire retardant, based on a 38,000 m^3/day influent flow rate with low-, medium-, or high-strength wastewaters. Percentages refer to P recovery rate relative to plant influent. Struvite production costs for 15%, 25%, and 40% P recovery are reported values from Egle et al. (2016) for MagPrex, Ostara, and REM-NUT, respectively. Cost for struvite incorporation into hydrogels is an additional 8.32 USD/kg P.

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