Supporting Information S1 Data for:

Integration of silicate minerals for ammonium and phosphate removal with an on-site wastewater treatment prototype.

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A. Media properties

Table S1. Polonite components in % of weight in dry condition provided by the supplier information [1].

| Components | % weight in dry conditions |
|------------|----------------------------|
| SiO₂       | 40.2                       |
| CaO        | 42.6                       |
| MgO        | 0.7                        |
| Al₂O₃      | 4.3                        |
| Fe₂O₃      | 1.9                        |
| K₂O        | 0.7                        |
| Na₂O       | 0.1                        |
| Total (Sum)| 90.5                       |

Table S2. Polonite properties provided by the supplier information [1].

| Property                             | Value                              |
|--------------------------------------|------------------------------------|
| Size of pellets                      | 2 – 6 mm                           |
| Adsorption capability P              | Up to 12%*                         |
| Porosity                             | 45%                                |
| Dry density                          | 730 g dm⁻³                         |
| Initial pH                           | > 12                               |
| Specific surface area [3]            | 14 m² g⁻¹                          |

*Theoretical biding. Depends on design and usage.

Table S3. Clinoptilolite components in % of weight provided by the supplier information [2].

| Components | % weight |
|------------|----------|
| SiO₂       | 66.70    |
| CaO        | 1.33     |
| MgO        | 0.27     |
| Al₂O₃      | 11.48    |
| Fe₂O₃      | 0.90     |
| K₂O        | 3.42     |
| Na₂O       | 1.80     |
| MnO        | 0.02     |
| TiO₂       | 0.13     |
Table S4. Clinoptilolite properties provided by the supplier information [2].

| Property                          | Value                                      |
|-----------------------------------|--------------------------------------------|
| Clinoptilolite content            | 97%+                                       |
| Silica/Alumina ratio              | 5.8/6.4                                    |
| Silicon/Aluminum ratio            | 5.1/6.4                                    |
| Cation exchange capacity (CEC)    | 1.6 – 2.0 meq g⁻¹                          |
| Size                              | 8 x 14 mesh                                |
| Size                              | 1.00 x 1.41 mm                             |
| Pore diameter                     | 4.0 – 7.0 angstroms                        |
| Specific surface area             | 40 m² g⁻¹                                  |
| Specific gravity                  | 1.89                                       |
| Bulk density                      | 57 – 60 lbs ft⁻³                          |
| pH stability                      | 3.0 – 10.0                                 |
| Hardness                          | 4.0 – 5.0 Mohs                             |
| Swelling index                    | Nil                                        |
| Thermal stability                 | 1292 °F (700 °C)                           |
| Crushing strength                 | 176 kgs cm⁻²                               |
| Wet attrition (AVG)               | 6 – 7 %                                    |
| Pore volume                       | 15%                                        |

Figure S1. (left) Polonite, particle size 2 – 6 mm. (right) Clinoptilolite, 8 x 14 mesh.
B. Clinoptilolite and Polonite sorptive capacity

Figure S2. Bath data at various media loadings fitted to Langmuir-Freundlich isotherm model. Media loading correspond to 0.1, 0.25, 0.5, 1.0, 2.5, and 5 g of sorptive media in 50 mL of GAC-L. (a) NH$_3$ concentration ranged from 104 – 188 mg L$^{-1}$, clinoptilolite loading ranged from 2 to 100 g L$^{-1}$, pH was not controlled, and contact time = 24 h. (b) PO$_4^{3-}$ concentration ranged from 51.4 – 67.8 mg L$^{-1}$, Polonite loading ranged from 2 to 100 g L$^{-1}$, pH was not controlled, and contact time = 24 h.
As shown in Figure S2, batch sorption data were model using Langmuir-Freundlich isotherm model. In our experiments, it is impossible to control the initial concentration of $\text{PO}_4^{3-}$ and $\text{NH}_3$ in the treated wastewater (GAC-$l$). Hence, the data set used resembles the effect of using controlled initial concentrations of the sorbate by varying the sorbent media loading. The experimental data was fitted using Langmuir-Freundlich’s isotherm model (Fig. S2):

$$q = \frac{Q_m \ast (K \ast C)^n}{1 + (K \ast C)^n}$$

where $q$ is the amount of adsorption at equilibrium, $Q_m$ is the adsorption capacity of the system, C is the aqueous phase concentration at equilibrium, K is the affinity constant for the adsorption, and n is the index of heterogeneity. As shown in Figure S2, the calculated clinoptilolite sorption capacity is $23.01 \pm 8.77$ mg NH$_3$ g$^{-1}$, and the calculated Polonite sorption capacity is $2.78 \pm 0.51$ mg PO$_4^{3-}$ g$^{-1}$. These $Q_m$ values are similar to the estimated sorption capacities $20.0$ mg NH$_3$ g$^{-1}$ and $3.2$ mg PO$_4^{3-}$ g$^{-1}$ for Clinoptilolite and Polonite, respectively, for the lowest-loading batch experiment ($2$ g L$^{-1}$) at 24 h contact time (see Fig. 3). For clinoptilolite, the model has a fit with $R^2 = 0.99$ likely due to cation exchange being the main sorption mechanism which has a minimal effect on the pH during the sorption process. On the other hand, for Polonite the model has a fit with $R^2 = 0.66$; this could be explained by the change in pH affecting the speciation of PO$_4^{3-}$ during the course of the experiments.
Figure S3. Clinoptilolite loading: 0.1, 0.25, 0.5, 1.0, 2.5, and 5.0 g in 50 mL of treated water samples for 2 h and 24 h. Initial NH$_3$ concentration ranged from 104 – 188 mg L$^{-1}$. 
**Figure S4.** Polonite loading: 0.1, 0.25, 0.5, 1.0, 2.5, and 5.0 g of Polonite in 50 mL of treated water samples for 2 h and 24 h. Initial $\text{PO}_4^{3-}$ concentration ranged from 51.4 – 67.9 mg L$^{-1}$.

Clinoptilolite and Polonite sorptive capacity depends on the prior treatment the water samples have gone through, the media loading, and the contact time. (Fig. S3) Clinoptilolite sorption capacity for the lowest loadings (0.1, 0.25, and 0.5 g) and the longest contact time (24 h) varies from 8 to 16 mg $\text{NH}_3$ g$^{-1}$ in BW-1 and UF-1; meanwhile the sorption capacity in GAC-1 and EC-1 under the same conditions is 20 mg $\text{NH}_3$ g$^{-1}$. For large loadings (1.0, 2.5, and 5.0 g) the sorption capacity is 2 to 5 mg $\text{NH}_3$ g$^{-1}$ for all water types regardless of the contact time (2 h or 24 h). The low sorption capacity values are due to an excess of clinoptilolite compared to the $\text{NH}_3$.
available for sorption. (Fig. S4) Polonite sorption capacity at low loadings (0.1, 0.25, and 0.5 g) with the longest contact time (24 h) ranged from 1.8 to 4.2 mg PO$_4^{3-}$ g$^{-1}$ for all water types. For large loadings (1.0, 2.5, and 5.0 g) regardless of the contact time (2 h or 24 h) Polonite sorption capacity remained at 0.1 to 1.6 mg PO$_4^{3-}$ g$^{-1}$. Even though, Polonite performance is affected by the water type used (Fig. 4) its sorption capacity is mostly unaffected because Polonite main sorption mechanism is precipitation.

**Figure S5.** Polonite loading: 0.1, 0.25, 0.5, 1.0, 2.5, and 5.0 g in 50 ml of EC-l for 2 h. Data shows three data sets for loadings: 0.1, 0.25, 1.0, and 5.0 g.

Polonite particle size is not uniform (Fig. S1) which increases the variability in its sorption performance at small loadings. At small loadings, big particles could reduce the overall available surface area for sorption making sorption results vary from one experiment to another as shown in Figure S5 for 0.1 g and 0.25 g of Polonite. At larger loadings, the average available surface area in the particles becomes more uniform as shown in Figure S5, where the data points for three separate experiments overlap for loadings 1.0 and 5.0 g.
C. Evaluation of regeneration solutions and nutrient recovery

![Graph showing regeneration solutions and nutrient recovery](image)

**Figure S6. Polonite control experiments:** Only desorption cycles were performed in during this experiment. Polonite loading is 10 g in 100 mL of new 1 M regeneration solution for each desorption cycle for 2 h. (left) PO\(_4^{3-}\) was measured in the regeneration solution after each cycle. (right) Polonite was dried in an oven at 150 °C for 12 h and weighed after each desorption cycle.

Control experiments for Polonite regeneration were performed to understand the possible structural damage caused to Polonite by the regeneration solutions. Polonite was placed in the regeneration solutions without a prior sorption cycle; then the regeneration solution was tested for PO\(_4^{3-}\), and Polonite was dried and weighed. Figure S6 shows that HCl causes Polonite to lose a significant amount of mass throughout each desorption cycle, and causes an increase in the PO\(_4^{3-}\) detected in the regeneration solution. All the other regeneration solutions (UPW, NaCl, KOH, and NaOH) do not cause Polonite to lose mass nor to contribute PO\(_4^{3-}\) to the regeneration solution. In Figure S6, the slight decrease in mass of Polonite when exposed to UPW, NaCl, KOH, and NaOH can be explained by the loss of small Polonite particles throughout the multiple washes with UPW.
Polonite goes through between cycles.

**Figure S7.** *Experiment.* Polonite loading: 10 g. Sorption cycles: 100 mL of GAC-l water for 2 h. Regeneration cycles: 100 mL of new 1M HCl solution for 2 h. *Control experiment.* Polonite loading: 10 g. Only regeneration cycles were performed for the control experiment with 100 mL of new 1M HCl solution for 2 h. During the control experiments the amount of PO$_4^{3-}$ desorbed from the Polonite itself due to HCl was recorded. *Adjusted data.* Adjusted data is a result of subtracting the amount of PO$_4^{3-}$ desorbed during the control experiment from the raw experiment data. Initial concentration of PO$_4^{3-}$ was 51.4 mg L$^{-1}$.

Polonite’s structural integrity is damaged during media regeneration with 1 M HCl. The damage is evident in Polonite’s mass loss throughout each regeneration cycle as shown in Figure S6. Polonite mass decreased from 10.00 g to 7.06 g after the first regeneration cycle, then to 6.31 g after the second regeneration cycle, and finally to 5.98 g after the third cycle. Polonite mass loss contributed PO$_4^{3-}$ to the regeneration solution causing a high measurement of desorbed PO$_4^{3-}$ after a sorption cycle. To estimate the amount of PO$_4^{3-}$ desorbed from Polonite itself by HCl, a control experiment in which Polonite only went through regeneration cycles was performed. Figure S7
shows the adjusted measurements for PO$_4^{3-}$ desorption by subtracting the amount of PO$_4^{3-}$ desorbed from Polonite alone from the experimental data, which contains desorbed PO$_4^{3-}$ from Polonite and from the prior sorption cycle. The obtained adjusted data points show similar desorption results as those obtained for the other regeneration solutions as shown in Figure 7.

**Figure S8.** Results of nutrient sorption/desorption across six cycles using (top) 1 M HCl as the regeneration solution for clinoptilolite and (bottom) 1 M KOH as the regeneration solution for Polonite. For each sorption cycle, 0.5 g of media was exposed to 150 mL of GAC-l water for 2 h. For each desorption cycle, the same media was exposed to 50 mL of fresh regeneration solution for 2 h. Initial nutrient concentrations were NH$_3$ = 140 mg L$^{-1}$ and PO$_4^{3-}$ = 35.2 mg L$^{-1}$. Each data point is the average of three replicate experiments (some error bars are smaller than symbols).
Figure S9. Results of nutrient sorption/desorption across six cycles using (top) 1 M HCl as the regeneration solution for clinoptilolite and (bottom) 1 M KOH as the regeneration solution for Polonite. For each sorption cycle, 0.5 g of media was exposed to 150 mL of GAC-l water for 2 h. For each desorption cycle, the same media was exposed to 50 mL of fresh regeneration solution for 2 h. Initial nutrient concentrations were NH$_3$ = 140 mg L$^{-1}$ and PO$_4^{3-}$ = 35.2 mg L$^{-1}$. Each data point is the average of three replicate experiments (some error bars are smaller than symbols).

Clinoptilolite NH$_3$ sorption capacity is not diminished by desorption cycles with 1 M HCl. Clinoptilolite desorbed an average of 24.4 ± 2.8% NH$_3$ from GAC-l each sorption cycle (Fig. S8). As shown in Figure S8, clinoptilolite is capable of desorbing 86.4 ± 2.9% of all NH$_3$ sorbed.
throughout six sorption/desorption cycles. In Figure S9, the cumulative mg NH$_3$ g$^{-1}$ sorbed/desorbed increased in parallel as most sorbed NH$_3$ is desorbed during the regeneration cycle. For Polonite, PO$_4^{3-}$ sorption is highest (22.4 ± 0.6%) during the first sorption cycle and then decreases to an average value of 8.2 ± 0.7% for subsequent sorption cycles. During the first desorption cycle KOH can only recover 32.3 ± 2.0% of the sorbed PO$_4^{3-}$ due to irreversible precipitation in Polonite. During subsequent cycles PO$_4^{3-}$ is sorbed by weaker, reversible sorption mechanism on Polonite surface resulting in ~75% of PO$_4^{3-}$ recovered during desorption cycles. Polonite cumulative mg PO$_4^{3-}$ g$^{-1}$ sorbed starts reaching a plateau with each subsequent cycle as more PO$_4^{3-}$ g$^{-1}$ is not desorbed each cycle; it is expected that with a longer cycle number cumulative mg PO$_4^{3-}$ g$^{-1}$ sorbed/desorbed will reach a plateau as all sorption cites that could be regenerated would have been exhausted.

References

[1] What is Polonite? 2020 [cited 27 January 2022]. In: Polonite Nordic [Internet]. Sweden: Polonite Nordic AB 2020. Available from: https://polonite.se/about-polonite/

[2] Technical data overview. 2018 [cited 27 January 2022]. In: KMI Zeolite [Internet]. Nevada: KMI Zeolite 2018. Available from: https://www.kmizeolite.com/technical-data/

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