

REMOVAL OF SEWAGE PHOSPHORUS BY ADSORPTION AND MINERAL PRECIPITATION, WITH RECOVERY AS FERTILIZING SOIL AMENDMENT

Craig Jowett¹, Irina Solntseva², Susan Glasauer², Lingling Wu³ and Chris James¹

ABSTRACT

Sand filters loosely adsorb 15 – 35% total phosphorus from septic tank effluent, with likely more adsorbed by soils in septic system leach fields. Although iron oxide and clay minerals in soils increase adsorption, P adsorbed by minerals may still be readily mobilized. Mineral forms of P are desirable to ensure stability, and do occur in certain soils when first adsorbed. The *Waterloo EC-P* method mimics processes that lead to P immobilization in mineral soil, but bypasses the intermediary step of adsorption onto minerals. Iron dissolved electrochemically reacts with phosphate ions (PO_4) and precipitates on a filtration medium as a crystalline phase, without production of P-rich sludge. Long-term field tests demonstrate phosphorus removal rates of 90 – 99% in sand, soil and synthetic foam filters, with mass balance results conforming to electrochemical theory. The crystallization of the insoluble Fe- PO_4 mineral vivianite, identified by SEM and XRD, suggests stable phosphorus removal from residential sewage. Recovery and re-use of the vitreous silicate medium (VSM) that retains the P precipitate as a fertilizing soil amendment is being investigated. Comparative soil leaching and corn plant growth studies show that retention of P in the VSM reduces P leaching, and that the amendment is equivalent to or better than commercial superphosphate fertilizers. This technology and process is shown to effectively reduce P in final effluent discharging to the natural environment, and shows promise of re-use as a fertilizing soil amendment.

Keywords

Agriculture, Fertilizer, Phosphorus, Recovery, Sewage, Soil Amendment, Vivianite

INTRODUCTION

Removal of phosphorus (P) from sewage systems is vital where residences are near freshwater rivers or lakes, or where fractured bedrock can channel nutrients quickly to groundwater and surface water. Soil is the receiving body for on-site system dispersal, and successful treatment and acceptance into the soil is critical to minimize surface breakout of septic tank effluent, which enhances the nutrient content of stormwater runoff to lakes. This is especially important in clay soil where raised beds are prone to surface breakout. However, even when subsurface dispersal is successful, certain soils, e.g., those low in aluminium and iron oxides, typically remove only a small fraction of the P introduced.

The precipitation of relatively insoluble P-bearing minerals will sequester P in the soil (e.g., Robertson 1995) or other filtration medium. This paper presents updated field results from *Waterloo EC-P* technology, an iron dissolution + filtration system, and demonstrates that P is

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removed to very low values before entering groundwater. We confirmed that the iron-phosphate mineral vivianite forms and sequesters P in a solid phase above the water table. A high rate of P removal is achieved with the *EC-P*, even using filtration materials that remove little P by adsorption processes only.

To provide context to the *Waterloo EC-P* process, this paper begins with a review of earlier work to remove P at individual residences. This includes removal via the formation of Fe-Al-rich 'B-horizon' soil, a discussion of historical data on P adsorptive removal by clear septic sand (without fines or iron oxides), and evidence showing that P previously adsorbed on septic sand is subsequently leached into groundwater, using results from multi-year field studies. This is followed by a presentation of the results from the *EC-P* system. The paper concludes with a study in which the filtration medium from the *EC-P* process, a waste product, is shown to be an effective fertilizing soil amendment for corn in a greenhouse trial.

PHOSPHORUS REMOVAL BY SEPTIC SOIL ADSORPTION

Individual Septic System Phosphorus Removal

Removal of P by Fe & Al: Conventional sewage phosphorus removal processes by Al- or Fe-based chemical addition purposely generate a P-rich sludge. The sludge is separated to remove the phosphorus physically for off-site treatment (Brandes 1976), although high-P sludge is welcome at fewer municipal treatment plants. An Al- or Fe-based reactive submerged medium can be used for P adsorption (Hutchinson & Jowett 1997; Heufelder & Mroczka 2006), even for individual residential septic systems. The resulting effluent pH is typically highly alkaline. When depleted, the P-rich medium is again taken off-site for disposal; treatment is challenging due to its chemical makeup. Mineralizing the P in the soil leach field is an option without disposal issues.

Natural 'B-Horizon' Soil Formation: B-horizon soil is formed when degraded iron silicates release Fe^{2+} ions into solution in the upper A-horizon soil, aided by decomposing organic matter (Figure 1). The dissolved iron percolates downwards and precipitates, primarily as oxidized ferric iron oxides and hydroxides, in the underlying B-horizon mineral soil. Reactive phosphorus dissolved in water passing through the B-horizon soil binds chemically to iron oxides to ultimately form iron-phosphate minerals, and these reactions can be very quick (e.g., Schulte & Kelling 1996; Barber 2002). Because Fe-P minerals have very low solubility under both aerobic and anoxic conditions (Hansen & Poulsen 1999; Barber 2002), phosphorus that exists below septic system leach fields is thus removed from the hydrologic cycle and kept out of groundwater and adjacent surface water bodies (e.g., Robertson 1995).

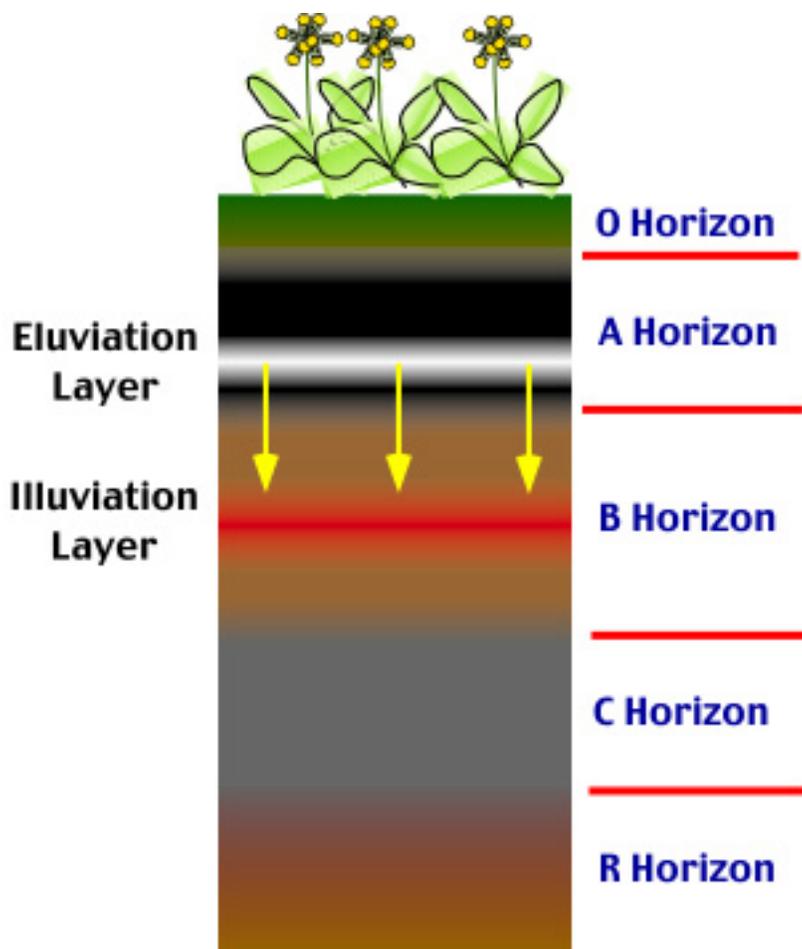


Figure 1. Soil horizons showing movement of soluble Fe^{2+} from A-horizon Soil to B-horizon soil (www.physicalgeography.net).

Soil organic matter in A-horizon soil degrades to form CO_2 and carbonic acid ($\text{H}_2\text{CO}_3 = \text{H}^+ + \text{HCO}_3^-$), whose protons (H^+) help break down Fe-rich silicate minerals, releasing ferrous ions (Fe^{2+}) into solution. In the oxidizing B-horizon soil, ferrous iron converts to ferric iron (Fe^{3+}), which readily precipitates as the characteristically coloured yellow, red, and brown hydroxides.

Stable, insoluble Fe-P minerals form in both aerobic and anoxic conditions, as e.g., strengite $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ in oxidizing, ferric Fe^{3+} conditions, and as vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ in reducing, ferrous Fe^{2+} conditions. Strengite has a solubility product constant $K_{\text{sp}} \approx 10^{-22}$ and vivianite has $K_{\text{sp}} \approx 10^{-36}$. These K_{sp} values are very low (compare to e.g., calcium carbonate with $K_{\text{sp}} \approx 10^{-9}$), indicating that these minerals are highly stable in typical soil environments (see Schulte & Kelling 1996; Barber 2002).

Al- or Fe-rich hydroxides in natural 'B-horizon' soils adsorb reactive P when placed below a standard leach field. In this case, the P is left *in situ* to potentially crystallize as insoluble minerals (Robertson 1995; 2003; 2008), although substantial P can be released when oxygen and pH conditions change (e.g., Patrick & Khalid 1974). While this latter soil-based method has low maintenance and no disposal or re-treatment issues, there is no assurance that preferential flow paths do not develop to by-pass the reactive soil, or that insoluble P-based minerals form to keep P out of the groundwater.

Keeping P out of Stormwater: Berkowitz (2013) describes surface water sampling in small watersheds in rural North Carolina, with various housing densities, including undeveloped forested watershed. Septic systems contributed more soluble nitrogen (N) than did forested areas, suggesting septic origin, and concentrations increased with higher population densities. However, the overall contribution of N and P was not substantial until storm events occurred which increased N and P concentrations by 1 – 2 orders of magnitude. These results indicate that successful soil-based septic systems which maintain sewage below ground do remove nutrients to a large degree, but failing septic systems that break out to surface will add large amounts of nutrients during storm events. The highly variable nature of soil chemical and physical properties does not, however, provide assurance that substantial P attenuation will occur.

Leaching of Adsorbed Phosphorus

Adsorption by Clear Sand: Conventional leach fields made of clear sand that receive septic tank effluent remove 15 – 35% of phosphorus (e.g., Figure 2). If the association of P with mineral surfaces is weak, it is susceptible to subsequent leaching (Robertson 1995; 2003). Results from the three-year sand filter study (1999 – 2002) in the Environmental Technology Initiative (ETI) program in Massachusetts (MASSTC 2003) demonstrate this. Following the standard for groundwater studies (e.g., Robertson 1995), only soluble PO₄-P was analyzed in the effluent from buried pan lysimeters, because total phosphate (TP) may be contaminated by soil particles. Total P is, however, analysed in septic tank effluent, including soluble and solid-bound P, to provide a representative value of the sewage entering the sand filter. A maximum P removal value is thus obtained, as TP would be equal to or higher than PO₄-P. This sand removed an average of (up to) 26.2% P between the septic tank effluent and the 600 mm deep pan lysimeter.

A similar multi-year study by Chowdhry (1974) on a variety of 750 mm deep sand filters demonstrated rates of TP removal of 14 – 29% from septic tank effluent. Although the published data is only summarized with percentile values, the overall median value is estimated at 18.4% TP removal. During the trickle flow-dosing test period, the two finer sands averaged 30.8% TP removal, and the three coarser sands averaged 15.8% TP removal. The percent removal declined by different extents when large doses of wastewater were pumped to the sand filters, especially in the coarsest sand filter.

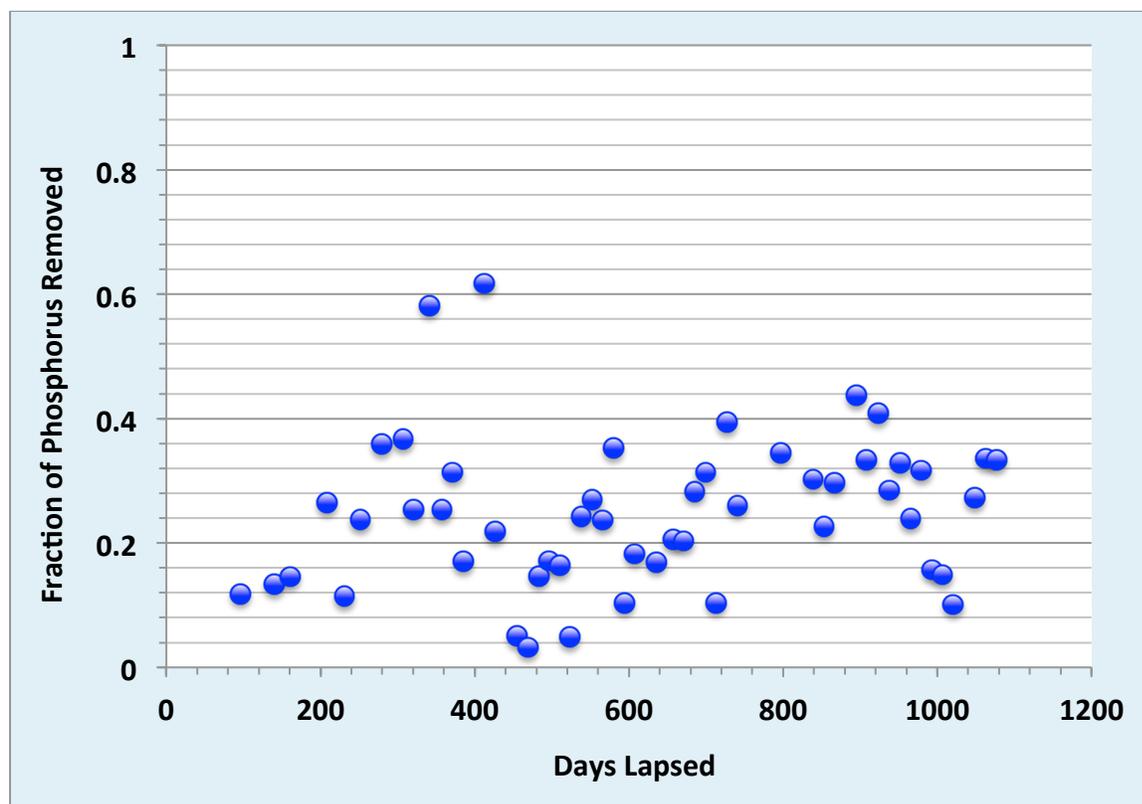


Figure 2. Phosphorus removed in Massachusetts single-pass sand filter between TP of septic tank effluent and $\text{PO}_4\text{-P}$ of sand filter effluent $(\text{TP}_{\text{inf}} - \text{PO}_4\text{-P}_{\text{eff}})/\text{TP}_{\text{inf}}$ in 24" depth pan lysimeter.

Leaching of Previously Adsorbed Phosphorus: The potentially ephemeral nature of adsorbed P is illustrated by long-term sampling at School BB in Ontario, Canada. A pan lysimeter was placed below the 250-mm layer of fine sand in the disposal bed receiving filtered sewage (cBOD & TSS < 5 mg/L; $\text{PO}_4\text{-P}$ = 7 – 8 mg/L). For two years, the sand removed ~30% of $\text{PO}_4\text{-P}$. After an *EC-P* unit was installed to remove P from the wastewater to ~0.5 mg/L $\text{PO}_4\text{-P}$, the sand began to *contribute* phosphorus to a value of ~1.0 mg/L (Figure 3). The formation of vivianite in the open-cell polyurethane foam biological filter preceding the sand layer is discussed below.

After a year of leaching phosphorus from the sand, the low-P influent passed through the sand with little change in concentration, and ~0.1 mg/L $\text{PO}_4\text{-P}$ entered groundwater. The clear sand temporarily retained its adsorbed phosphorus, and this was subsequently removed when geochemical conditions changed. The key issue for permanent P sequestration is to precipitate relatively insoluble minerals and to avoid temporary adsorption.

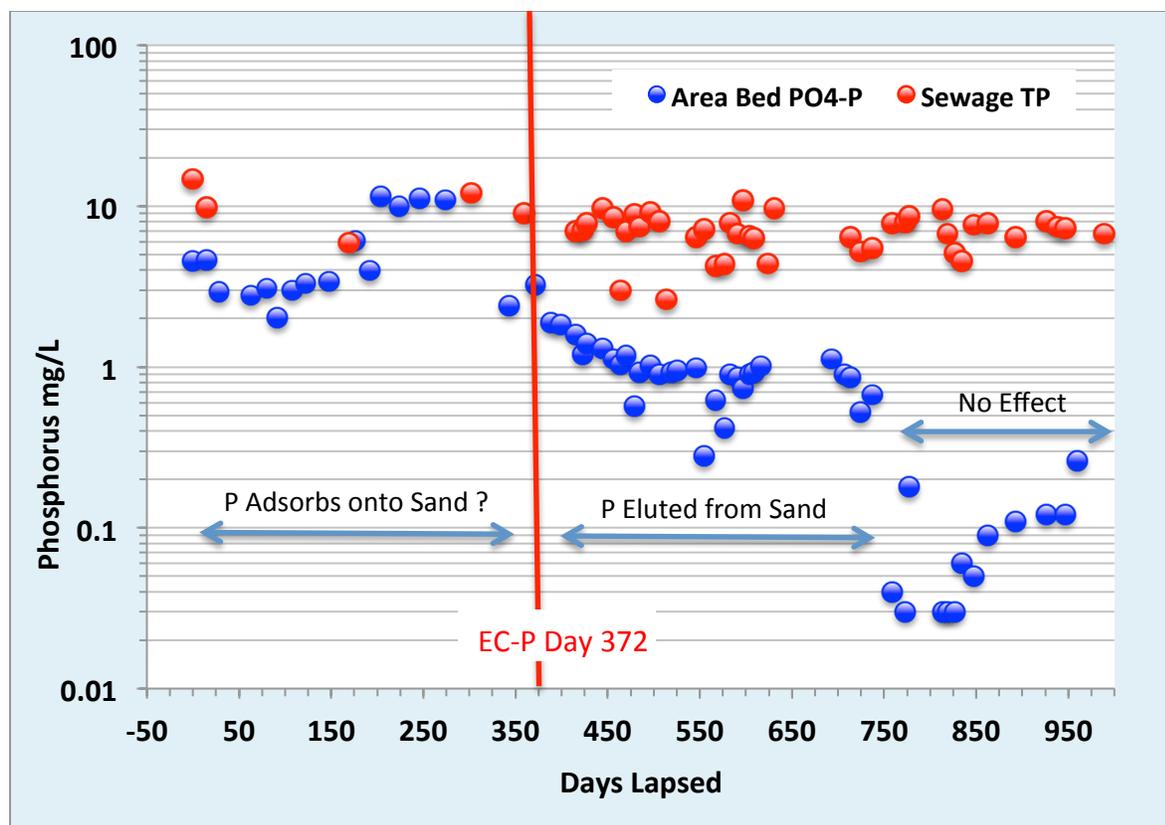


Figure 3. Dissolved phosphorus ($\text{PO}_4\text{-P}$) below clear sand layer demonstrates P adsorption until Day 372, followed by elution of adsorbed phosphorus until it is leached out by Day 750.

PHOSPHORUS REMOVAL BY *EC-P* PROCESS

Background and Field Studies

Mimicking B-Horizon Soil Formation: High P-removal rates are now being attained in septic systems using sacrificial anode electrochemistry followed by filtration (*Waterloo EC-PTM*, patents pending). Iron is dissolved into the sewage stream, where it reacts with phosphorus to form insoluble P-based minerals. This is akin to natural soil-forming processes but without the intervening hydroxide-adsorption stage (Xu 2010; Jowett et al. 2013; 2014). Filtration media used to date include polyurethane foam, coarse sand, and sandy loam soil. The technology is abiotic, thus relatively independent of temperature, consumes ~0.5 kW-hr per day per residence, is largely independent of water characteristics, has no sludge or reactive medium issues, and has no adverse effect on pH.

Predicting TP Removal with *EC-P*: During early testing at an Ontario truck stop, the *EC-P* treated several cubic metres of Waterloo Biofilter effluent each day, returning the Fe-P rich effluent back to the septic tank to be dosed again to the Waterloo. As Fe and P accumulated in the filtration medium over time, the Waterloo effluent became weaker in TP, from the initial TP ≈ 19 mg/L to TP ≈ 12 mg/L near the end of the testing (Figure 4), even though only a small percentage of the total flow was being treated.

Knowing the sewage details at this facility provided an opportunity to test another theory: that of predicting TP removal as outlined in Xu (2010). If the test analytical data conform to standard physics and chemistry theory, the technology gains greater confidence and more general acceptance. The simulation uses actual hydraulic flow rates of influent sewage, of re-used water (this facility uses Waterloo effluent for toilets & urinals), and of water passing through the experimental systems. These data are combined with the concentrations of TP in the three water types. By using physical relationships of Fe-P chemical bonding, the TP concentration in the Waterloo effluent is determined and compared to the actual laboratory analyses (Figure 4).

In Figure 4, the energy input (solid red line) increases from the starting date of September 27 2010 to Day 112, and TP in Waterloo effluent (black dots) is thereby depleted at a rate conforming to that predicted by theory (solid purple line). This outcome confirms that known physical-chemical theory does apply, that the technology is designed and operated appropriately, and that the mass of TP removed can be predicted.

After Day 112, the energy input (solid red line) is decreased and the predicted concentration of TP (solid purple line) increases as expected along with the actual concentration (black dots) until the end at March 7 2011. The fluctuations seen in the solid purple line around Day 112 are due to anomalously low flows followed by a 7-fold increase in sewage volume from the facility.

After the experiments were discontinued and energy to the system shut off on March 7 2011, the TP in the Waterloo effluent had returned to normal values of 18 – 20 mg/L by July – August 2011. The simulated theory predicted these concentrations as well, based on the flow rates and zero energy input to the TP removal system.

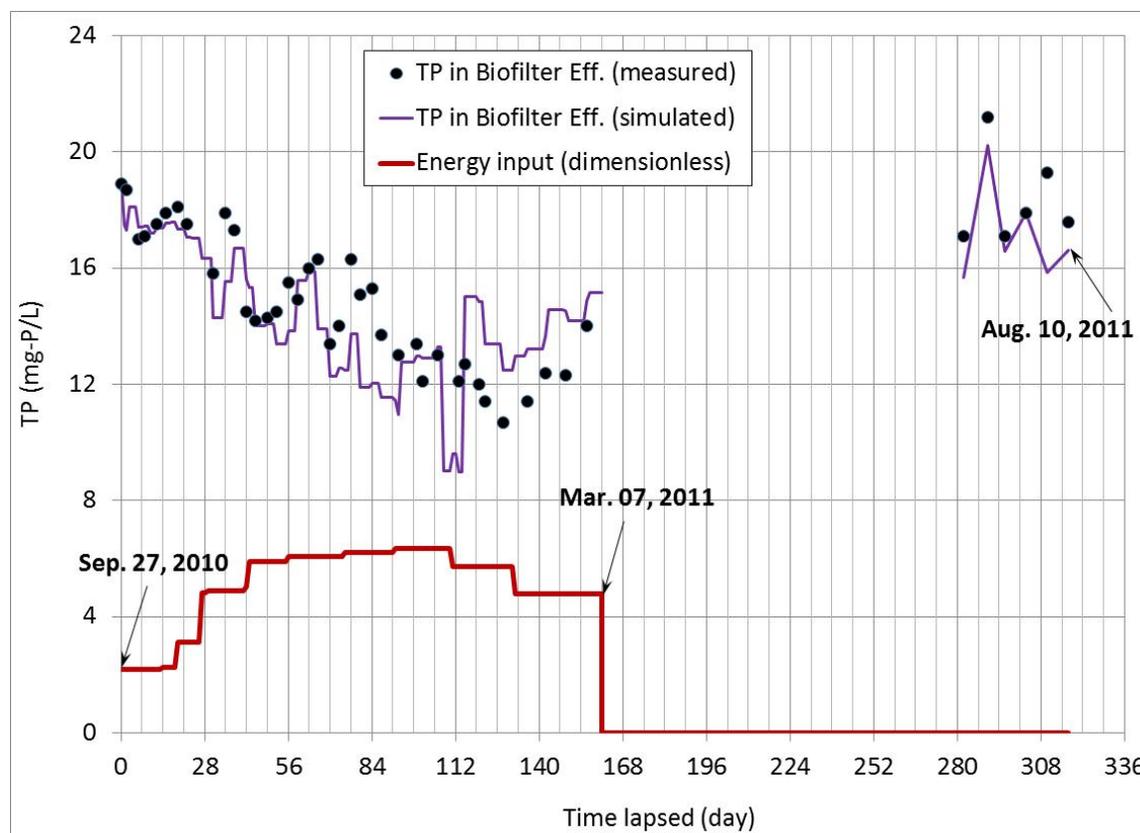


Figure 4. Theory of predictability of TP removal applied in bench-scale testing (from Jowett et al. 2013).

Addition of Mineral Volumes: The volume of mineral precipitate accumulating in the upper 0.5 m of soil is small, calculated at <2% of pore space in soils over 20 years of operation at peak design flow, and the effective plugging volume will be less if mineral concretions are formed, as is expected.

EC-P + Soil Field Results: An on-going three-year study at Massachusetts Alternative Septic System Test Center facility using the *EC-P* technology retrofitted into a conventional septic tank + soil leach field demonstrates that the *EC-P* + 300 mm of soil removes 98% TP (Figure 5), increasing to >99% if 600 and 900 mm depths are included. The soil is a mixture of 60% coarse sand used in the Environmental Technology Initiative sand filter study (Figure 2) and 40% silt. The fraction of P removal in the *EC-P* + soil averages 99.2% TP removal after passage through 600 mm of soil, compared to 26.2% P in 600 mm clear sand filter (Figure 2).

The *EC-P* was removed at Day 680 to determine the background P-attenuation potential of the soil, and is reflected in the increased values over time after removal.

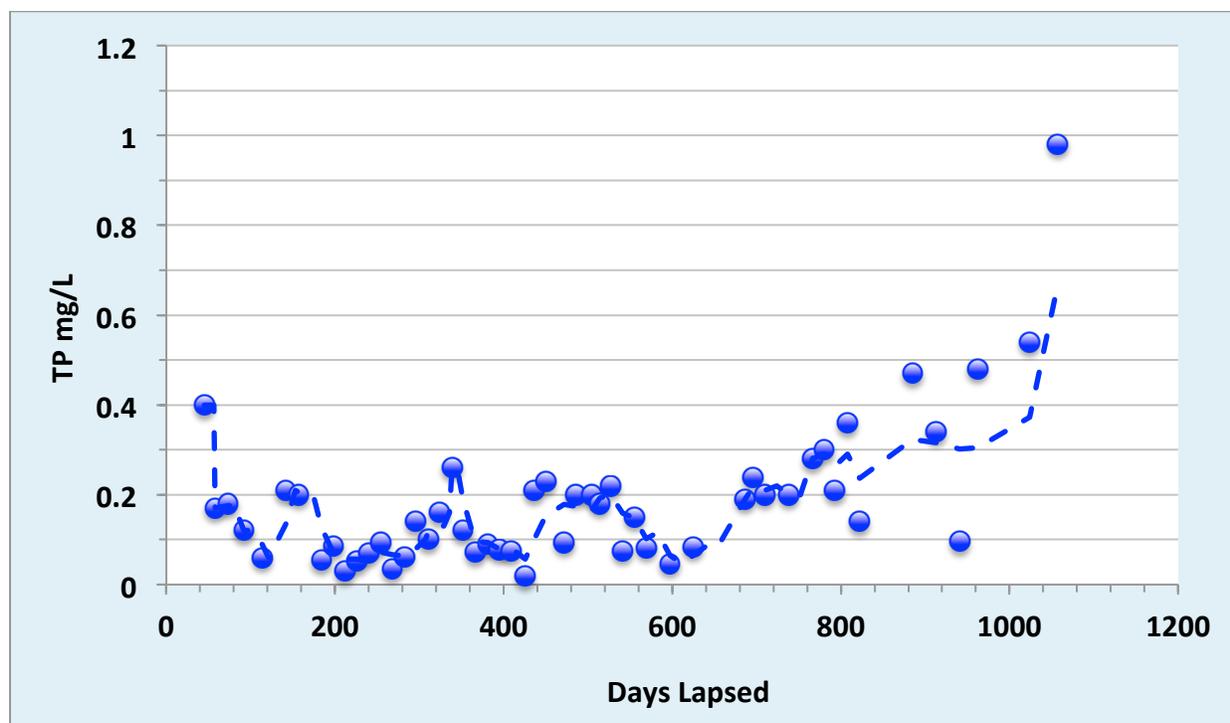


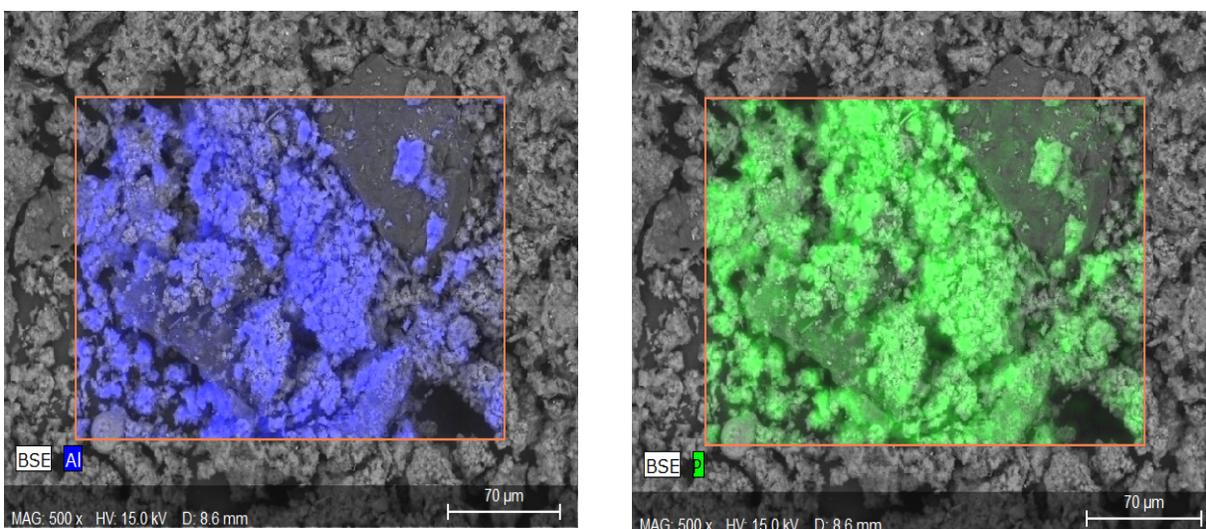
Figure 5. Pan lysimeter TP results at 300 mm soil depth below septic tank effluent with *EC-P* to soil leach field. Results of 600 and 900 mm pan are removed for clarity. *EC-P* was removed on Day 680 to determine the removal of background P by soil.

Identification of Fe-P Minerals

We conducted studies to identify whether the formation of solid phases contributes to immobilization of P in the EC-P filter. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) studies of accumulated solids in *Waterloo Biofilter* filtration medium were carried out by Sun and Wu (2014) at the University of Waterloo supported by an NSERC Canada Engage grant (Wu 2014). The Waterloo Biofilter foam filter medium was sampled at two schools in Ontario using *BD GasPak EZ* anaerobic collection pouches to prevent oxidation of minerals as prescribed in Wu (2014). Both samples were taken at 300 mm depth in the filter medium. School MV uses an alkali-aluminum chemical to remove phosphorus, while School BB uses the iron-based *EC-P* unit.

SEM Studies: The samples were freeze-dried and analyzed for physical structures and chemical elements by SEM. Following different attempts at sample preparation, the dried Al-based sediment-sludge from School MV was physically knocked out of the foam, whereas School BB foam samples were sectioned into thin slices for examination.

At School MV, Al – P association showed that the P was chemically bound with Al, but as an amorphous compound (Figure 6). Although the system was several years old and should have had time to form crystals, no identifiable crystalline Al-P mineral fraction was evident and XRD over a 24-hour period showed that little or no well-crystallized structures were present.



a. Aluminum

b. Phosphorus

Figure 6. SEM element maps of School MV foam medium showing close association of Al and P in amorphous non-crystalline mass. Not shown are strong correlations of K, Na, and Si.

However, at School BB where the iron-based *EC-P* is used, SEM identified crystalline Fe-P compounds (Figure 7), formed within 18 months. Initial XRD analysis indicated that hydrated crystalline minerals of the calcium oxalate weddellite and the iron phosphate vivianite formed. Both minerals are consistent with an anoxic environment.

Vivianite was identified by XRD in settleable sludge produced by adding ferrous iron to phosphate solution in an anaerobic environment (Masood & Recht 1971). In their batch experiments, pH ranged from 6 to 9, with optimum removal by precipitation (and flocculation) at

initial pH = 8 (their Experiment 8). Iron phosphate precipitates on 100 μm screens were amorphous to XRD after 15 minutes of mixing, but crystalline after 5 hours. Using secondary effluent at pH = 8 (their Experiment 15), ferrous iron precipitated vivianite after 1 hour of mixing, identified based on colour change from light green to blue upon exposure to air.

Precipitation of low-solubility crystal cements like vivianite provides confidence that removal of phosphorus from the hydrologic cycle occurs by the formation of low-solubility compounds.

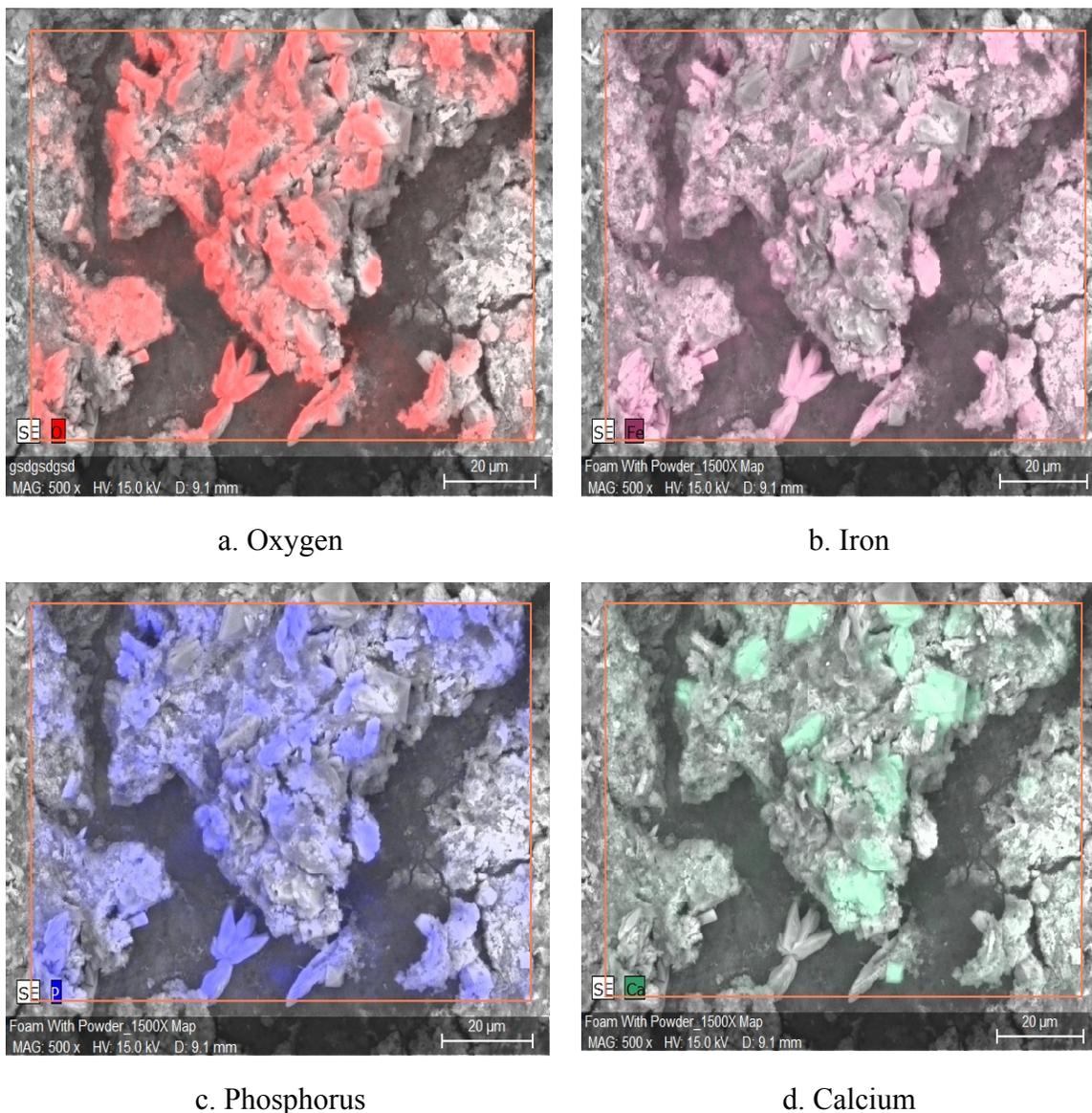
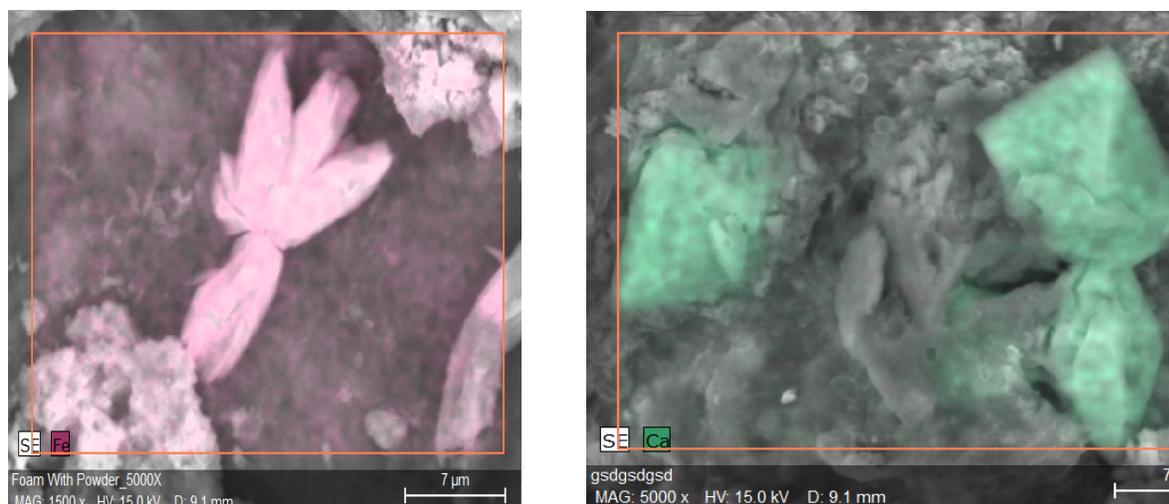


Figure 7. SEM element maps of School BB foam medium showing the close association of Fe and P in bladed prismatic crystals of vivianite, with Ca associated with double-tetrahedral crystals of weddellite (Figure 8). Oxygen is associated with Fe, P and Ca.



a. Iron in vivianite

b. Calcium in weddellite

Figure 8. Close-up views of Figure 7 SEM element mapping of Fe-P rich vivianite (a) and weddellite (b) as identified by X-ray diffraction scans in Table 1.

XRD Studies: Smears of accumulated solids from School BB were prepared by freeze-drying and analyzed by X-ray diffraction (XRD) technique to determine crystallinity and identify precipitated minerals. Due to the small quantity of material, a series of 1-hour scans over 24 hours was carried out to remove background interference and accentuate distinguishing peaks.

Results indicate no calcite or dolomite crystals but do verify calcium oxalate crystals known as weddellite $\text{CaC}_2\text{O}_4 \cdot 8\text{H}_2\text{O}$, which has a tetragonal crystal habit similar to the Ca-rich crystal in Figure 8. It is found in urinary tracts as ‘kidney stones’, in sea floor mud, and in peat sediments. Also verified were bladed crystals of the ferrous Fe – P mineral vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$, as anticipated in Xu (2010) and Jowett et al. (2013). Both minerals are hydrated and both form in oxygen-poor environments. These XRD scan output results are depicted in Table 1 and Figure 9.

Table 1. Pattern list of XRD scan of Brisbane filtered solids identifies the calcium oxalate weddellite and Fe- PO_4 mineral vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$.

Visible	Ref. Code	Score	Compound Name	Displacement [$^{\circ}2\text{Th.}$]	Scale Factor	Chemical Formula
*	98-003-0783	59	Weddellite	0.000	0.648	$\text{C}_2 \text{H}_{4.75} \text{Ca}_1 \text{O}_{6.375}$
*	98-003-0645	22	Vivianite	0.000	0.248	$\text{H}_{16} \text{Fe}_3 \text{O}_{16} \text{P}_2$

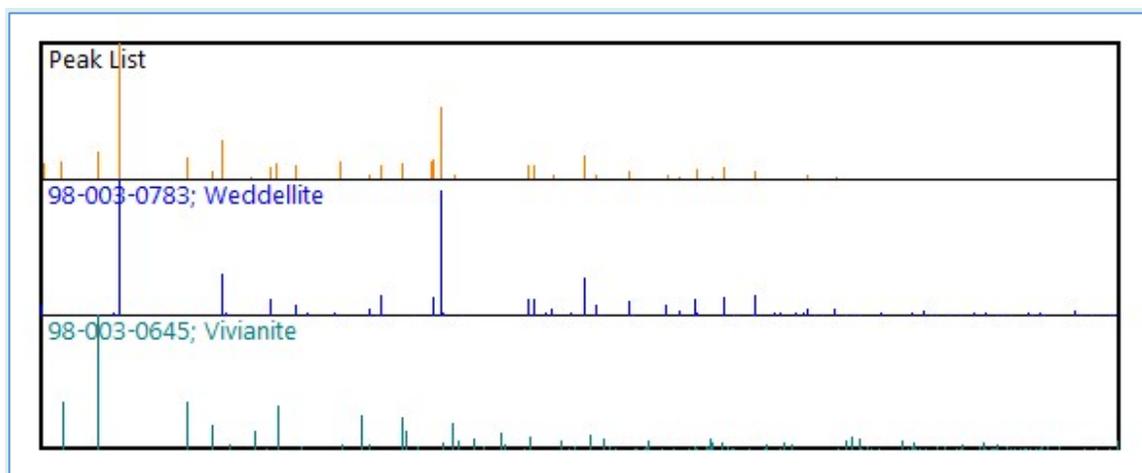


Figure 9. XRD peak scans compared to database scans indicate best estimate as weddellite (hydrated calcium oxalate) and vivianite (hydrated ferrous phosphate) minerals.

The presence of crystalline minerals confirms that mineral cementation occurs as a result of the *EC-P* technology, and that phosphorus is tightly bound within a mineral structure. Vivianite is very insoluble, with a solubility constant of $\sim 10^{-29}$ M. This important finding indicates that precipitation of crystalline minerals occurs relatively quickly, within 18 months, and that the phosphorus removed by the *EC-P* process can be successfully removed from the hydrologic cycle.

SUITABILITY OF *EC-P* PHOSPHORUS AS FERTILIZING SOIL AMENDMENT

Comparative Leaching of Soil Phosphorus

Leaching of Phosphorus from Amended Soil: While sequestration of P by adsorption processes and the formation of precipitates is the primary goal to maintain groundwater quality, there is also potential for recovery and re-use. Solntseva & Glasauer (2015) conducted studies at the University of Guelph using sorptive materials removed from an *EC-P* system to investigate (1) phosphorus solubility in soils, and (2) the use of vitreous silicate material (VSM) treated with sewage effluent as a fertilizing soil agent. The VSM, suitable in itself as a soil amendment, was used as the filtration medium accepting septic tank effluent (STE) after the *EC-P* process at School BB. As a comparative benchmark, VSM with STE from School ER with no *EC-P*, was also used.

To determine the retention of P in the different types of VSM treatment, leaching experiments were performed using two soils that have different texture characteristics (sand-loam and silt-loam) to investigate the impact of texture on P mobility.

Shredded VSM material was mixed with sand-loam and silt-loam soils in pots, and water was added periodically in an amount to displace one pore volume for each dosing period. Effluent leachates were analyzed for water-soluble orthophosphates (H_xPO_4-P ; $x=0-2$) using an Astoria flow-cell analyzer. After two weeks, the soil in the pots was analyzed for water extractable and total phosphates (reverse aqua regia method) by inductively coupled plasma mass spectrometry

(ICP-MS). The values of $H_xPO_4\text{-P}$ in collected leachates were recalculated based on the total amount of orthophosphate removed from each pot per gram of added material (Figure 10).

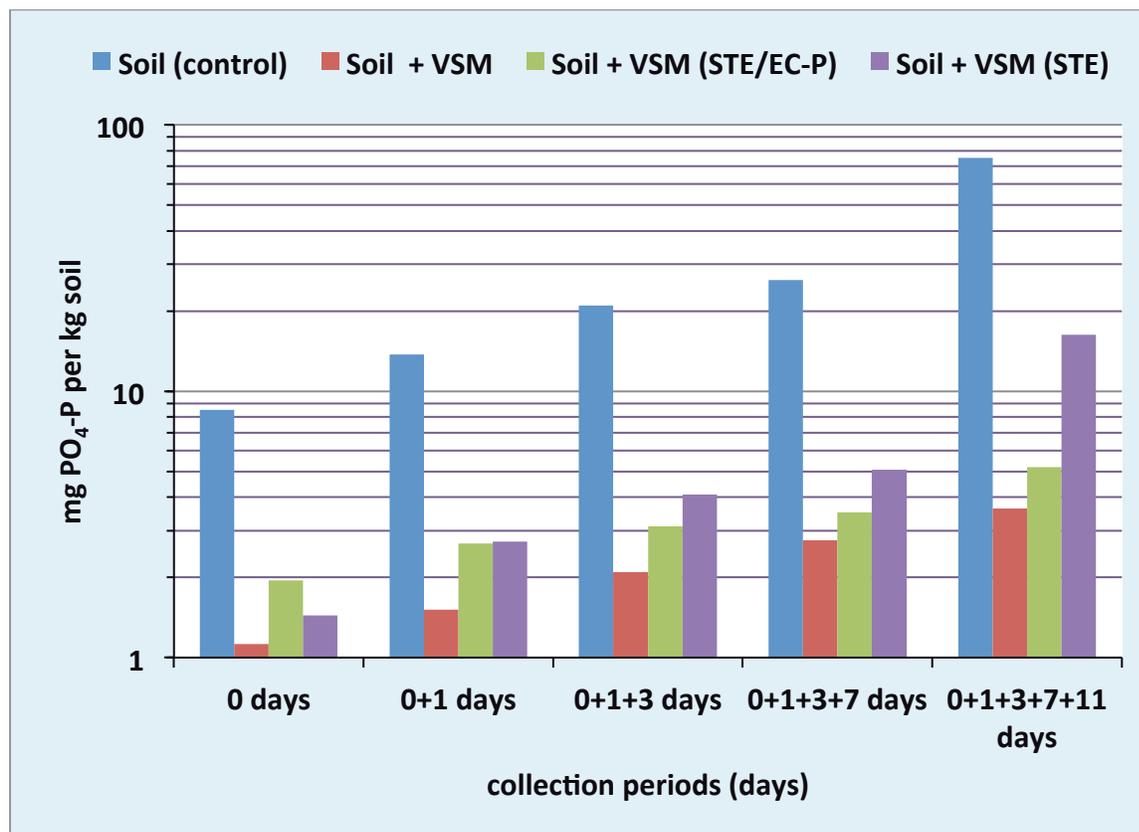


Figure 10. Cumulative mass of $PO_4\text{-P}$ leached from silt-loam soil over 11 days, shows that addition of the VSM treatment alone and VSM + *EC-P* retards phosphorus leaching into the groundwater. Results are similar for sand-loam leaching.

Over a two-week period, the control soil with nothing added leached out much more P than the soil with barren medium or with *EC-P* medium (School BB), indicating that the presence of the VSM itself retains P in the soil. Water extracted substantially more P from the STE-soil than from the STE-*EC-P* soil, suggesting that P associated with the VSM (STE) is more soluble than with the VSM (STE-*EC-P*), indicating a more insoluble form of P in the *EC-P* treatments. Alternatively, the VSM material may have adsorbed soluble P enough to retard its leaching out.

Agronomic Study on Corn Plants

Rationale and Experimental Methodology: The plant response of corn, an important Ontario crop, was studied in soil amended by different VSM and *EC-P* treated materials and compared to soil amended by conventional mineral fertilizers. Low phosphorus sandy loam soil was used from Ontario croplands where corn is cultivated and where mineral fertilizer is required. Soil phosphorous deficiency suppresses root development especially during the early stages. Corn is a fast-growing species and was chosen to provide quality results within the short time frame of this NSERC Engage project.

Five different soil treatments using the sandy-loam soil in four-kg pots were prepared for the plant growth study in a University of Guelph greenhouse (Solntseva & Glasauer 2015). The treatments consisted of; (a) natural soil with nothing added, (b) soil with only shredded virgin VSM added, and (c) soil with only P fertilizer added. These controls were compared to; (d) soil with shredded VSM having received STE for 4 months at School ER with no *EC-P*, and (e) soil with shredded VSM having received *EC-P* STE for 4 months at School BB. The materials were added on the basis of equivalency to P_2O_5 fertilizer applied at a conventional rate of 80 kg P per hectare.

Clean VSM was included to eliminate any effect of the material itself that tends to keep P from leaching with water, and better compare with other treatments. The VSM material is very porous and its presence in the pots affects critical physical properties of the soil such as aeration, bulk density, etc., which in its turn might affect chemical processes in the soil, as well as plant responses.

Five replicates of each of the five soil treatments were used, and each planted with six pretreated corn seeds of cultivar Pioneer P9675 AMXT. The soil was packed to equal bulk density of 1.2 g/cm^3 prior to planting. Six seeds were sown per pot at a uniform 1-cm soil depth, and after 10 days were thinned to three evenly spaced seedlings per pot. The pots were maintained under greenhouse conditions and were watered automatically each day according to crop requirements.

After two months, the plants were harvested and analysed for height, dry biomass and phosphorus content in plant tissues. The leaves and stems of each corn plant were dried in an oven at 65°C and ground into a homogeneous powder. For phosphorus analyses, samples were then dry-ashed in a muffle furnace at 500°C and the residue dissolved in 0.1 N HCL. Phosphorus content of the acid extract was measured using an automated Astoria-2 Flow Cell colorimeter.

Corn plant heights showed visible differences in growth within two weeks as a function of treatment, and this relationship was consistent to the end of the two-month study (Figure 11). The heights of the plants grown in soil that received mineral fertilizer (c) or the STE-*EC-P* VSM material (e) were comparable and were the tallest overall. Plants grown in soil with virgin VSM (b) or VSM (STE) (d) were shorter, and the control soil (a), which received no amendment, was the shortest. These differences demonstrate that P available from the *EC-P* process stimulates plant growth similar to conventional fertilizer. It also indicates that the virgin VSM material in itself enhances plant growth, perhaps connected to its ability to retain phosphorus during leaching experiments (Figure 10).

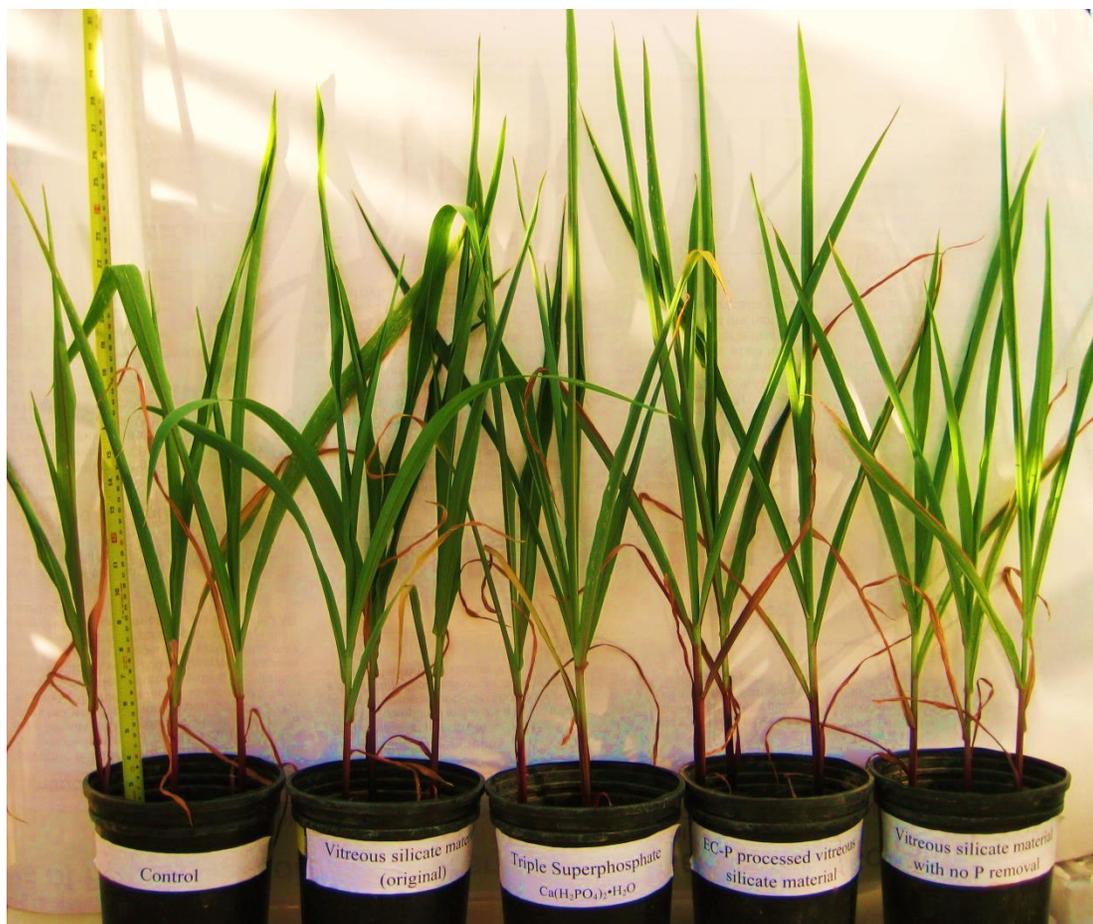


Figure 11. Corn plant growth study indicates that the VSM alone and the VSM (STE/EC-P) act as positive ‘fertilizer’ soil amendments compared to the control soil. Left to right: Control Soil (no amendments added to sand-loam soil); Soil + VSM (virgin medium); Soil + Triple Superphosphate $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$; Soil + VSM (STE/EC-P); Soil + VSM (STE).

Tukey’s multiple-comparison test was used to determine which means of the five populations (columns 1 to 5 in Figure 12) differ significantly from any of the other four means. At a probability of $P < 0.001$, the mean plant height of the soil control (column 1) after two months’ growth, differs from the soil + VSM (column 2), the soil + mineral fertilizer (3), and the soil + VSM (STE/EC-P) (4) populations. At $P < 0.01$, the control soil (1) and the soil + VSM (STE/EC-P) (4) populations differ from soil + VSM (STE) (5). All other differences are not significant at $P < 0.05$.

Identical Tukey relationships were found with the dry biomass populations depicted in Figure 13, except that the soil control (column 1) and the soil + VSM (STE) (5) were not significantly different at $P < 0.05$. For the relative mass of phosphorus taken up by the plants (not shown), there was no difference among populations 2, 3, and 4 at $P < 0.001$.

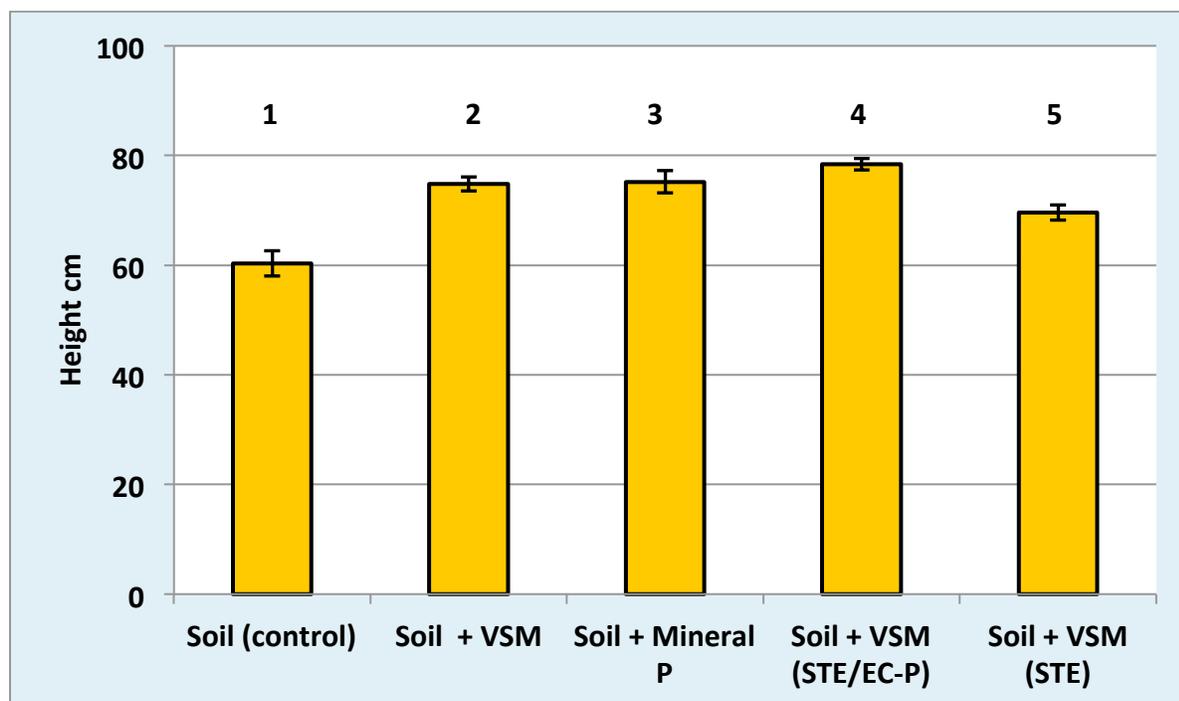


Figure 12. Height of corn plants after two months (mean of N = 15 for each of the 5 treatments; error bars represent Standard Error of the mean).

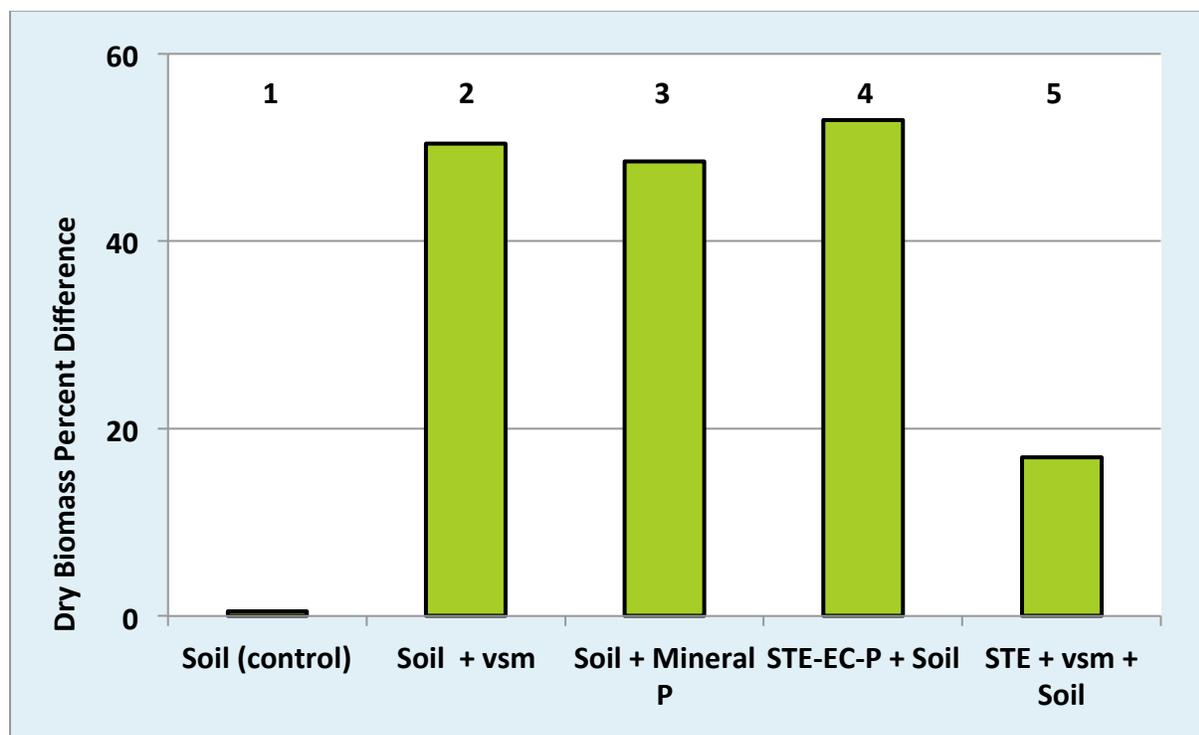


Figure 13. Percent difference of dry biomass in comparison to control treatment after two months (average of N = 15 for each of the 5 treatments).

Based on plant height, biomass, and phosphorus uptake in plant tissue, the data demonstrate that corn plants respond well to the VSM-based treatments, including untreated VSM, compared to the soil control (Figures 12 – 14). The mass of the dry plants was about 50% greater than the soil control as depicted in Figure 14.

The total uptake of phosphorus by plants in each pot was calculated by multiplying the phosphorus content per gram of dried biomass by dry biomass weight. The results reveal the plant response to the various treatments. The phosphorus uptake of the plants was about 8 – 16% greater than the soil control as depicted in Figure 14.

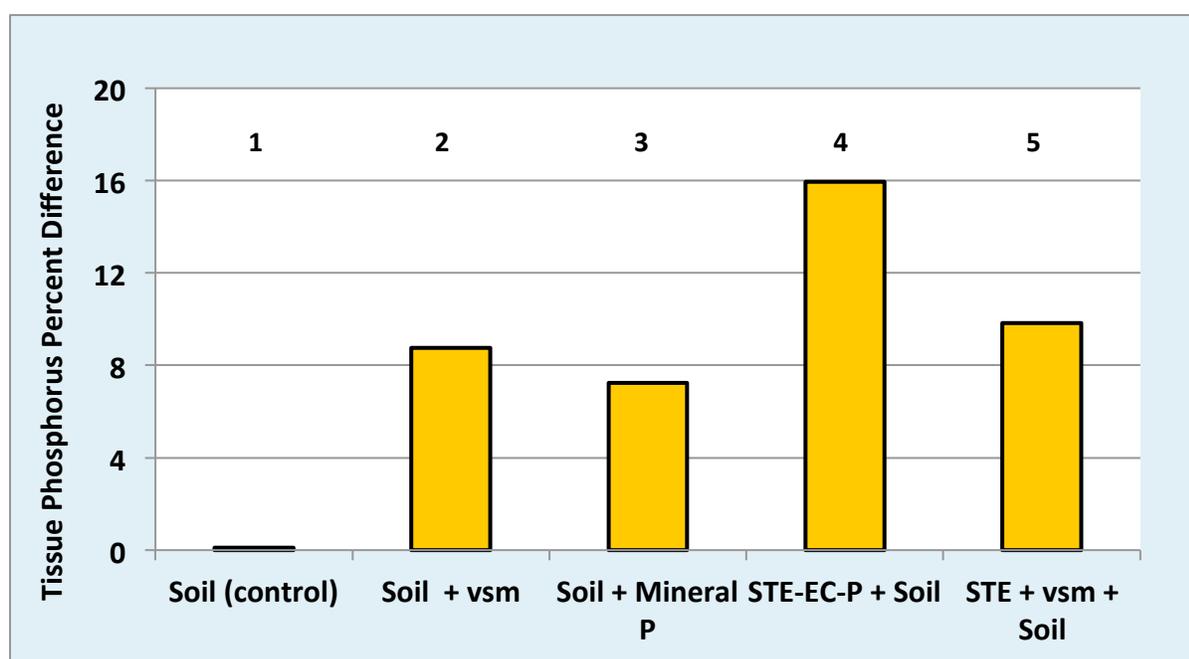


Figure 14. Percent difference of plant tissue phosphorus in comparison to control treatment after two months (average of N = 15 for each of the 5 treatments).

It is not known why the VSM itself, with no P added, is equivalent to the other treatments. A possible explanation is that it helps retain soil phosphorus against leaching (Figure 10) and thus provides a readily available supply of P to the plant roots. The phosphorus in VSM (STE) may be more soluble than in VSM (STE/EC-P) or when bound by VSM. If insoluble vivianite were also formed on the VSM (as on the Biofilter foam), would it be available for plant uptake. Fodoué et al. (2015) carried out similar plant studies using quarried mineral vivianite as fertilizer and found that soil chemistry was adequate to enable its use as a well-performing natural fertilizer.

Further study is required to understand the contribution of these different elements. The study supports, however, that phosphorus leaching can be minimized and retained in the soil for plant growth.

CONCLUSIONS

Conventional leach fields with clear sand or soil (no fines or Fe-rich material) can expect to remove 15 – 30% TP from septic tank effluent. In general, the finer the soil is, the higher the removal. Soils will remove nutrient constituents adequately from watersheds when sewage does not break out to surface. Clear sand is, however, shown to loosely bond sewage TP that can be subsequently leached out when geochemical conditions change.

A three-year study using iron-based *EC-P* technology in a conventional septic tank + soil leach field demonstrates that high phosphorus removals can be attained. More than 98% of the total phosphorus was removed at a depth of 300 mm and >99% at 600 mm and 900 mm depths. Gradual removal with depth suggests phosphorus is distributed through the soil profile and not concentrated at the soil-trench surface.

Where aluminum-based chemicals are used to remove TP in foam filtration medium, SEM and XRD studies of accumulated solids indicate formation of amorphous Al – P compounds, with no crystalline forms evident. Crystalline forms of Fe – P minerals were precipitated in the filtration medium after *EC-P* treatment, or were filtered from the effluent solution. Initial XRD analysis indicates that hydrated crystalline minerals of weddellite and low-solubility vivianite are formed, indicating that a more sustainable removal of phosphorus from the hydrologic cycle is attained.

Soil leaching studies show that VSM-based amendments retain soil P during leaching experiments, and that P accumulated on the *EC-P* VSM material promotes growth of higher and more robust corn plants compared to the control soil alone, and equivalent to superphosphate fertilizer amendment.

The *EC-P* technology and filtration is shown to effectively remove P from sewage before entering the natural environment, and shows promise of re-use as a fertilizing soil amendment.

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