The removal of glyphosate in agricultural runoff by hybrid constructed wetland mesocosms.

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Abstract Glyphosate is a commonly used herbicide in agriculture. However, glyphosate finds its way into the environment after application as it leaches or runs off into water bodies. Hybrid constructed wetland mesocosms consisting of surface flow wetland planted with duckweed and subsurface flow wetland planted with cattails and bulrush were used as a means for treatment of agricultural runoff containing glyphosate. Analysis of water samples after passing through the two-state wetlands was used to evaluate the removal of agrochemicals by wetlands and variation in removal with each pulse loading. The results indicated that removal of glyphosate by surface flow wetlands was 80%, 69%, and 59% for each pulsed event indicating the removal rate may decrease over time. However, the addition of subsurface flow wetland achieved 94%, 97% and 97% removal. Consequently, establishing or adding a hybrid flow component to existing wetlands may achieve higher removal of agrochemicals, like glyphosate. Evaluation of the nature-based passive treatment solutions to agricultural non-point source pollution is important to help keep our water safe and clean.

Keywords:

Pesticides, surface flow wetland, subsurface flow wetland, treatment wetlands, ecological engineering, nature-based solutions, agrochemicals, agricultural wastewater

Introduction

Agrochemicals are needed to produce food on a mass scale for an ever-growing world population. However, there is a recurring issue of agrochemicals, for example, pesticides, finding their way into the environment after application as they leach or runoff into water bodies, enter the atmosphere through spraying and volatilization, and persist in soil and water. According to the World Health Organization (WHO) and United Nations Environment Program (UNEP), there are 26 million poisonings and 220,000 deaths from pesticides annually worldwide.

Glyphosate is a popular herbicide that has been used extensively for decades worldwide. Glyphosate was first discovered in 1950 by Dr. Henry Martin, however its use as an herbicide didn't occur until years afterwards (Benbrook, 2016). Dr. John Franz of Monsanto Company discovered its herbicidal use in 1970 and glyphosate was sold as an end use product called "Round-

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up” in 1974 (Gandhi et al. 2021). Over time, glyphosate garnered popularity but the introduction of genetically engineered herbicide tolerant crops (GE-HT) made the herbicide even more useful. In 1996, the approval of GE-HT soybeans, corn, and cotton allowed farmers to apply glyphosate as a broadcast post emergent herbicide, extending the application period (Benbrook, 2016).

The National Agricultural Statistics Service (NASS) reported the rise in glyphosate use on soybeans in the U.S. from 1990 to 2014. In 1990, soybeans accounted for one-third agricultural glyphosate use but that rose to one-half by 2014. To further expound on this, NASS reported that the three major GE-HT crops (corn, soybeans, and cotton) accounted for about 200 million pounds of glyphosate used in 2014. The issue of extensive use of glyphosate is international. In 2014, the average rate of glyphosate applications per hectare per crop year was in the range of 1.5-2.0 kg/ha (Benbrook, 2016). That year, 22%-30% of globally cultivated cropland could have been treated with the amount of glyphosate applied.

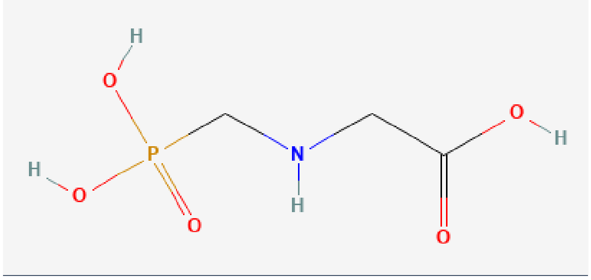

Fig. 1 Chemical structure of the glyphosate (NCBI, 2023)

Glyphosate is an amphoteric compound, which contains a 2° amino group in the center of the molecule with dibasic-phosphonic and monobasic-carboxylic acidic sites at the two ends (Figure 1) (Gandhi et al. 2021). Due to it having a linear carbon chain with a weaker bond, it is less persistent in the environment (NCBI, 2023). Commercial use of glyphosate herbicides contains the chemical in the form of liquid soluble salts. Glyphosate is applied in a variety of forms including isopropylamine salt, ammonium salt, diammonium salt, dimethyl ammonium salt, and potassium salt (Benbrook, 2016). These formulations enhance plant uptake and water solubility but contribute toward the toxicity of the herbicide (Gandhi et al. 2021). Glyphosate kills weeds by the destruction of the shikimate pathway by inhibition of 5-endpyravyl-shikimate-3phosphate synthase enzyme. This alters the production of important aromatic amino acids (Matozzo et al. 2020). This process results in the hampering of protein synthesis and growth, leading to cellular death (Salisbury and Ross, 1994).

Studies have shown glyphosate occurrence in the environment due to excessive application. A study found that glyphosate concentrations in freshwater systems were highest in the countries Argentina, Colombia, and Portugal at 105 ppm, 2.77 ppm, and 2.46 ppm respectively (Brovini et al. 2021). In Buenos Aires, Argentina glyphosate was found in concentrations of 0.10-0.70 ppm in waters and 0.5-5.0 mg/kg in soil and sediments (Peruzzo et al. 2008). These samples were taken from a soybean cultivation area located near tributary streams. Some literature suggests possible health and safety problems regarding glyphosate exposure to humans and the environment. Environmental studies have pointed out the effects of glyphosate on soil microbial communities, insects, and crustaceans (Benbrook, 2016). In soils, glyphosate is typically sorbed limiting its movement and has a half-life of 47 days (Tu et al. 2001). Glyphosate attaches to soil particles easily, meaning it may have the ability to persist in clay soils longer than sandy soils (Gandhi et al. 2021). However, the extended presence of glyphosate in soils has advantages and disadvantages. Soil ecosystems can be harmed by the application of this chemical, while some soil microorganisms may use it as a nutrient source (Kremer and Means, 2009; Haney et al. 2000; Wardle and Parkinson, 1990). In soils treated with glyphosate, increase in the population of a certain fungal species triggered diseases in plants being studied (Zobiole et al. 2011).

Due to over spraying on agricultural fields and spray drift, glyphosate can reach both surface and ground water primarily through runoff (Ruiz-Toledo et al. 2014). Glyphosate can interfere with water-soluble organic matter, soil particles, and minerals. These connections can support the colloidal associated transportation of glyphosate (Vereecken, 2005). Studies suggest that glyphosate contaminating surface and groundwater could hinder the quality of drinking water. Communities who are located closer to agricultural activity are at a higher risk of glyphosate contaminated water exposure (Cengiz et al. 2017).

The United States Environmental Protection Agency (EPA) has set the chronic reference dose of glyphosate to 1.75 mg/kg of body weight per day. However, the body of toxicological studies supporting the EPA chronic dose references dates to the early 1970s to mid-1980s (Benbrook, 2016). Recent studies have shown the toxicity of glyphosate in humans. In 2015, a review from the International Agency Research on Cancer classified glyphosate as an “probable human carcinogen” (IARC, 2015). A review of glyphosate and glyphosate-based herbicides toxicity depicted harmful effects on cells and DNA including possible cancer association, and in mammals, glyphosate contamination seems to disrupt cellular function, cause inflammation, and interfere with the immune system (Peillex and Pelletier, 2020). The main source of chronic exposure of glyphosate to humans could be from food as residues have been found in crops, drinking water, and livestock tissue (Benbrook, 2016).

Constructed wetlands have been studied as a cost-effective and passive means for removing glyphosate and other agrochemicals from farm wastewater and runoff (Liang et al. 2020). Within constructed wetlands, plants, microorganisms, and biofilms are essential for the dissipation of pesticides (Lv et al. 2017). Uptake and biotic transformation of pesticides by plants and microorganisms, including catalytic, photolytic, and hydrolytic transformations are components of the cumulative dissipation process performed by these systems (Braschi et al. 2021).

Hydrology and flow path divides wetlands into two main categories, surface flow and subsurface flow (Vymazal, 2007). Mimicking ponds or marshes, surface flow constructed wetlands consist of man-made ponds or tanks used to collect and treat runoff and wastewater (Li et al. 2018). Field scale models of surface flow wetlands include artificial ponds, lagoons, and ditch-ponds (Nakamura 2009; Ma et al. 2015). Hybrid constructed wetlands take the two main categories of wetlands and combine them to make a newly constructed wetland system. Hybrid systems typically contain an open water, surface flow tank and subsurface tanks with a vertical and or horizontal flow of water (Ali et al. 2018; Haydar et al. 2020). Both surface flow tanks and subsurface flow tanks in hybrid systems are usually planted with wetland vegetation, however, subsurface flow tanks usually contain a soil media.

Most of the literature on the use of hybrid constructed wetlands to remediate wastewater usually focus on the remediation of nutrients (ex. nitrogen and phosphorus), total suspended solids, fecal coliform, COD, and BOD (Herrera Melian et al. 2010; Serrano et al. 2011; and Saeed et al. 2019). Past research studying constructed wetlands for the removal of glyphosate included either surface flow wetlands or subsurface flow wetlands (Liu et al. 2019). This experiment adds to the body of literature by studying the removal of agrochemicals from agricultural runoff and wastewater using hybrid constructed wetlands using a combination of both surface flow and subsurface flow wetlands.

This study evaluated the hypothesis that the commonly used herbicide, glyphosate, is removed at a significantly higher rate in hybrid constructed wetlands than in a surface flow constructed wetland through the combined biophysiochemical processes occurring in hybrid constructed wetlands. The specific aims of this study included:

(i) Evaluate the removal of glyphosate in simulated agricultural runoff by surface flow constructed wetlands.
(ii) Compare the removal of glyphosate in surface flow wetlands and the hybrid wetlands.
(iii) Compare the removal of glyphosate per event under the multiple pulsed-loading events by the hybrid wetlands.

Methodology

Wetland Design

In this experiment, three hybrid-constructed wetlands were constructed and used for the treatment of influent water contaminated with glyphosate (Figure 2). Each hybrid wetland system consisted of an opaque horizontal surface flow tank and horizontal subsurface flow tank connected by pvc pipes. The length, width, and height of each tank were 0.9 m×0.3 m × 0.3 m, respectively. The simulated wastewater was sampled at the inlet (sampling point 1), after it passed the surface flow wetland (sampling point 2), and after it passed the subsurface flow wetland (sampling point 3).

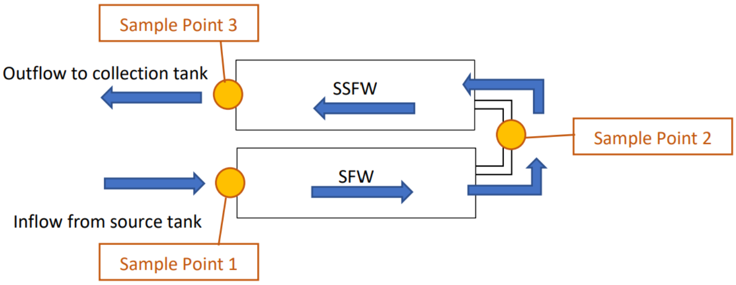

Fig. 2 Hybrid constructed mesocosm wetlands set-up in the greenhouse showing one of the three replicates.

For each surface flow wetland (SFW), 2.54 cm of sand was added at the bottom (Figure 3). Whereas each subsurface flow wetland (SSFW) consisted of media with 8.89 cm of coarse gravel, 13.97 cm of fine gravel, and 5.08 cm of sand from bottom to top. Since the total depth of the tank was 30.48 cm, around 2.54 cm "free board" was on the top for water (Figure 3).

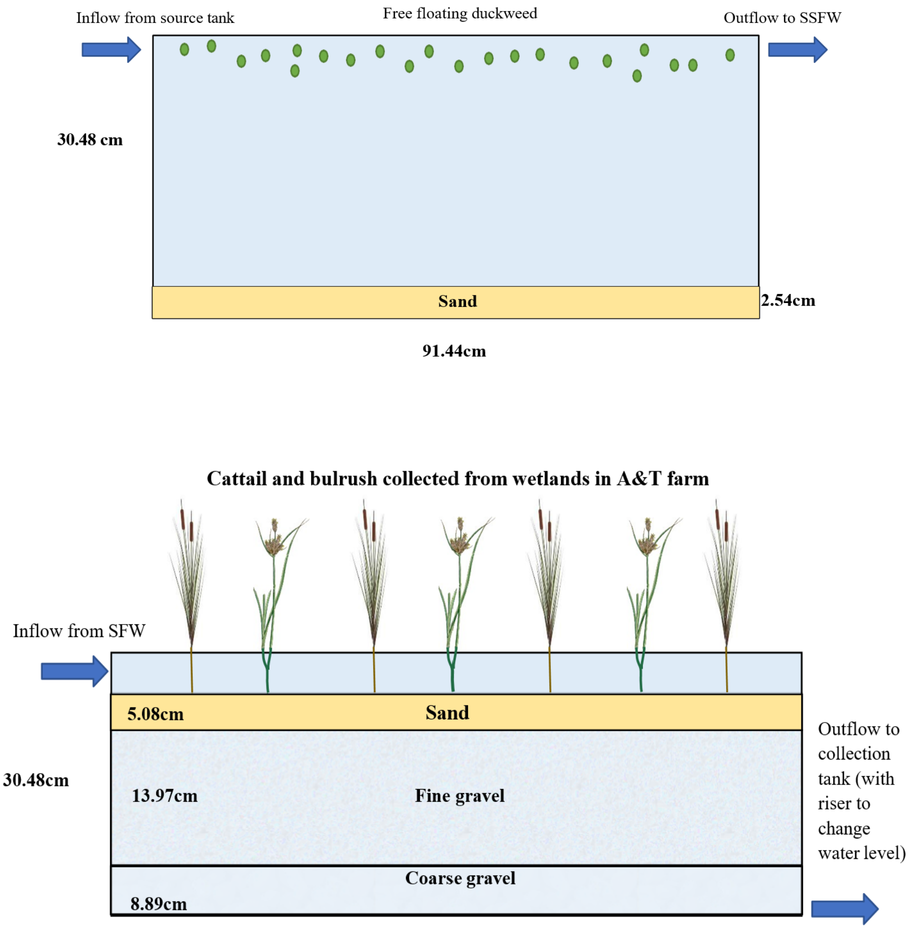

Fig. 3 Cross section of hybrid wetlands showing surface flow (top) and subsurface flow wetlands (bottom).

The duckweed for each surface flow system were obtained from Carolina Biological Supply Company. On the contrary, vegetation in the subsurface flow tanks contained cattails and bulrush obtained directly from a healthy wetland located on the North Carolina A&T State University Farm, located at 36°03'41.3"N 79°44'10.0"W. The plants were given an adaptation period in the wetlands to ensure their health.

Experimental Design

Glyphosate was purchased from ThermoFisher Scientific in its powder form. Pesticide treatments were prepared by weighing the chemical mass and dissolving it in reservoir water. Immediately afterward, water was pumped at the designed flowrate into each hybrid wetland system. The treatments were designed to mimic pulse events, in which a rain event would cause runoff from agricultural fields after pesticide application. The experimental design included three pulse events. Each pulse event began with 97.8 L of water being pumped, lasting 6 days. Afterwards for 7.5 days, tap water was pumped into the system to flush. This flushing was needed for water to continue passing through the wetlands to retain the functionalities of a wetland.

A peristaltic cartridge pump obtained from Antylia Scientific Company delivered the influent into each constructed wetland system. Each full system had a hydraulic retention time of 6 days with a full system flowrate of 16.3 L/d. Inflow tubing of the pump fed into the influent reservoir, which contained 97.8 L of simulated wastewater. The volume of water contained in the reservoir was calculated using ***Volume= flowrate*** × ***loading time*** × ***replications***. The chemical mass input of glyphosate was calculated through the equation ***Mass=spike concentration*** × ***flowrate*** × ***loading time*** × ***replications***. The chemical mass input was 1.956 g for a theoretical spiking concentration of 20 ppm. Based on the detection range of 0.1 ppm to 20 ppm, the actual measured concentrations of glyphosate in the influent ranged from 10 ppm to 15 ppm. Removal processes of hydrolysis, photolysis, and biodegradation could have been possible within the source tank (Sandy et al. 2013; Vymazal and Brezinova 2015).

Sample Collection and Preparation

During the 40-day study period, three spiking events for glyphosate were followed by flushing events (with only tap water influent). Throughout the experiment, grab samples were collected from each wetland at the influent and effluent section (figure 2). Samples were first taken on day 1 at 9:00 AM one day after initial exposure. The second sample was taken at 9:00 PM the same day. Afterwards, samples were taken at 9 AM on day 2, 3, 5, 7, 10, 13, 17, 21, 26, 31, 37, and 40 (Table 1). Samples were collected in clear glass vials, passed through nylon filter membranes, and analyzed in ion chromatography immediately. Samples that were not analyzed immediately were filtered, stored in a refrigerator at 4 ^{o}C, and analyzed within 3 days after collection.

Day	**Sampling Event**	**Spiking/Flushing Events**
0	0	Background Sample
1	1	Spiking

1	2	Spiking
2	3	Spiking
3	4	Spiking
4	No collection	Spiking
5	5	Spiking
6	No collection	Flushing
7	6	Flushing
8	No collection	Flushing
9	No collection	Flushing
10	7	Flushing
11	No Collection	Flushing
12	No Collection	Flushing
13	8	Spiking
14	No Collection	Spiking
15	No Collection	Spiking
16	No Collection	Spiking
17	9	Spiking
18	No Collection	Spiking
19	No Collection	Flushing
20	No Collection	Flushing
21	10	Flushing
22	No Collection	Flushing
23	No Collection	Flushing
24	No Collection	Flushing
25	No Collection	Flushing
26	11	Flushing
27	No Collection	Spiking
28	No Collection	Spiking
29	No Collection	Spiking
30	No Collection	Spiking
31	12	Spiking
32	No Collection	Spiking
33	No Collection	Flushing
34	No Collection	Flushing
35	No Collection	Flushing
36	No Collection	Flushing
37	13	Flushing
38	No Collection	Flushing
39	No Collection	Flushing
40	14	Flushing

Table 1 Sampling schedule used throughout the experiment.

Sample Analysis

Glyphosate was analyzed using an ICS-6000 under an anion system. The cartridge type was EGC 500 KOH with the concentration mode on a multi-step gradient. Columns included an AG11 guard column and AS11 analytical column. Method used a flowrate of 0.25 mL/min using an isocratic pump with a temperature of 30ºC. KOH concentration started at 10 mM and increased to 35 mM at 30 minutes, 10 mM at 33 minutes, and 10mM at 35 minutes. The total run time per sample was 35 minutes. A standard calibration curve was constructed using seven glyphosate standards ranging from 0.1 ppm to 20 ppm. Standards were made from diluting a 100 ppm glyphosate stock solution. The standard curve had an r^2 value of 0.99 or higher. The limit of detection (LOD) was 0.1 ppm.

Results & Discussion

On average, the surface flow wetlands removed glyphosate by 73% due to the processes of phytoremediation by duckweed and microbial degradation (Figure 4). The use of a hybrid system allows for increased diversity of macrophytes, therefore a possible increase in the rate of phytoremediation. For example, duckweed is a free-floating macrophyte that has been used in constructed wetland studies, primarily in surface flow wetlands such as in this experiment. A study looked at the use of *lemna minor* (duckweed) in reducing concentrations of imidacloprid, thiacloprid, dimethomorph, and myclobutanil in floating constructed wetlands (Pavlidis et al. 2022). Removal rates for water containing the pesticides and treated with *lemna minor* (duckweed) were 10.4% to 49.9% for imidacloprid, 38.8% for thiacloprid, 13.2% to 63.5% for dimethomorph and 60.8% for myclobutanil. Sand layers at the bottom of the surface flow tanks provided sites for adsorption. Compared to other authors, removal rates for organophosphate pesticides vary similar or higher than what was observed in this experiment. Moore et al. 2013 noticed an average removal of 75% for diazinon in their surface flow constructed wetlands. Blankenberg et al. 2007 observed an average removal of 38% for clofenvinphos in a similar set-up.

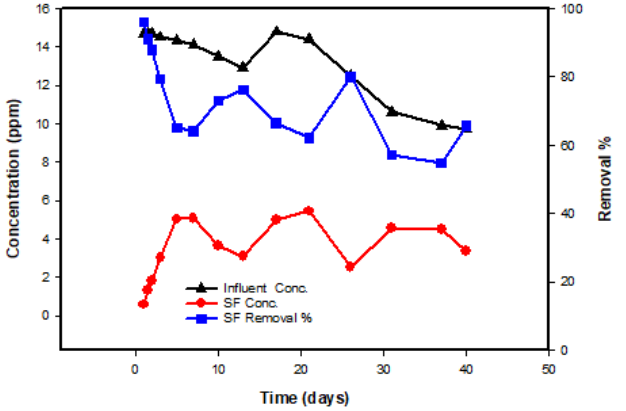

Fig. 4 Concentrations (primary y-axis) and removal efficiency (secondary y-axis) of the surface flow constructed wetlands with time.

When the concentration from the subsurface flow wetland was considered, the hybrid wetlands consisting of surface and subsurface flow wetlands outperformed the surface flow wetlands significantly (Figure 5). The concentrations in the effluent from the subsurface flow wetland were below the detection limit of ion chromatography (0.1 ppm).

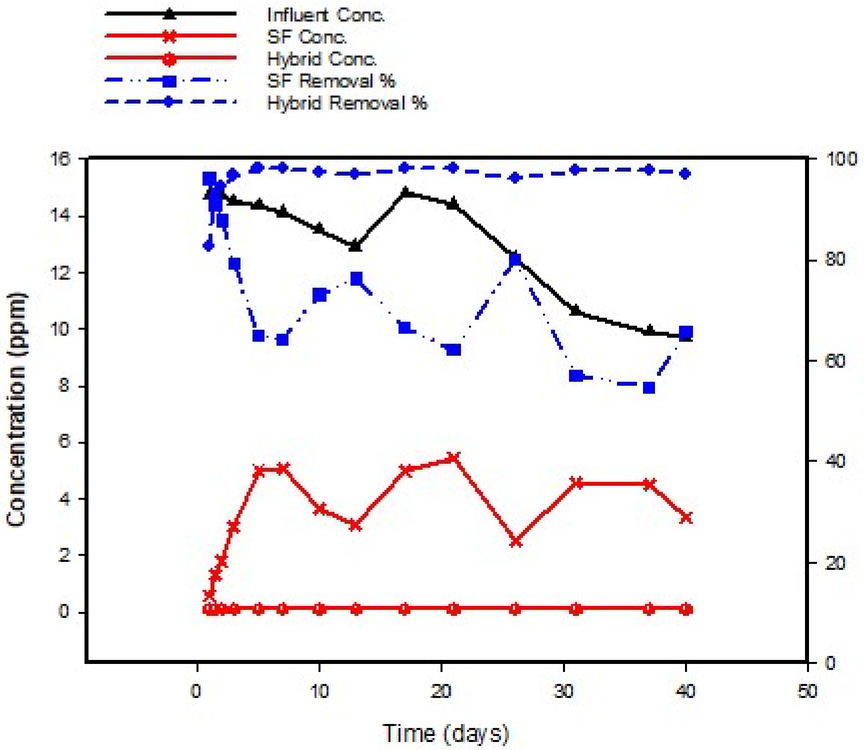

Fig. 5 Concentration (red; primary y-axis) and removal (blue; secondary y-axis) of glyphosate by surface flow constructed wetlands and hybrid constructed wetlands.

Hybrid constructed wetlands can use various design models of open water surface flow wetlands and subsurface flow wetlands. The hydrology and increased variety of removal processes in hybrid constructed wetlands support higher removal efficiencies (Figure 6). A study in Italy used a surface flow constructed wetland treating agricultural drainage water (Braschi et al. 2022). Hydraulic residence time was 6.7 days though mean dissipation was 50%, still lower than the removal efficiency of our hybrid wetland systems. The inclusion of a strict soil media could also factor in the higher removal efficiency of glyphosate in hybrid systems that utilize subsurface flow wetlands. In this experiment, coarse gravel, fine gravel, and sand were used as the soil matrix. A review article reported sand to have a relatively higher permeability for polar and ionic compounds to allow sufficient interactions, and higher organic material in soil producing better hydrophobic adsorption and supporting the growth of plants and microbes (Liu et al. 2019). The same review article also reported that gravel is frequently used in the mitigation of organophosphorus pesticides in constructed wetlands with higher conductivities (Dordio and Carvalho, 2013; Gorito et al. 2017; Li et al. 2014).

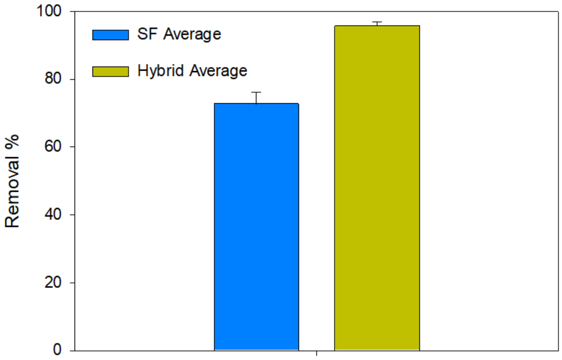

Fig. 6 Comparison of the removal efficiencies of the surface flow (SF) constructed wetlands and hybrid constructed wetlands.

As the source tank reservoir was emptied, concentrations gradually decreased towards the end of the spiking period. After the source tank was emptied, it was filled with tap water to flush the systems. The flushing of the systems allowed wetland functionalities to continue by having wet hydrology and functional plants. Each flushing lasted for 7.5 days, with glyphosate concentrations decreasing over time. Dilution from contaminant free influent water could have played a role in the decreased concentrations. Effluent from the surface flow wetlands decreased to as low as 2.5 ppm concentration during the flushing periods. Concentrations were shown to gradually decrease in the source tank, this being mostly evident in the third pulse event (Figure 5). Concentrations in the surface flow systems increased to about 5 ppm during the beginning of each spiking period. The results showed that with each pulse event, glyphosate concentrations of the surface flow wetlands gradually increased as simulated runoff entered the systems. However, the degradation in the source tank showed no major effect on the removal efficiency. Removal rates in the surface flow constructed wetlands decreased with each pulse event, though the removal rates of the hybrid constructed wetlands stayed level (Figure 7).

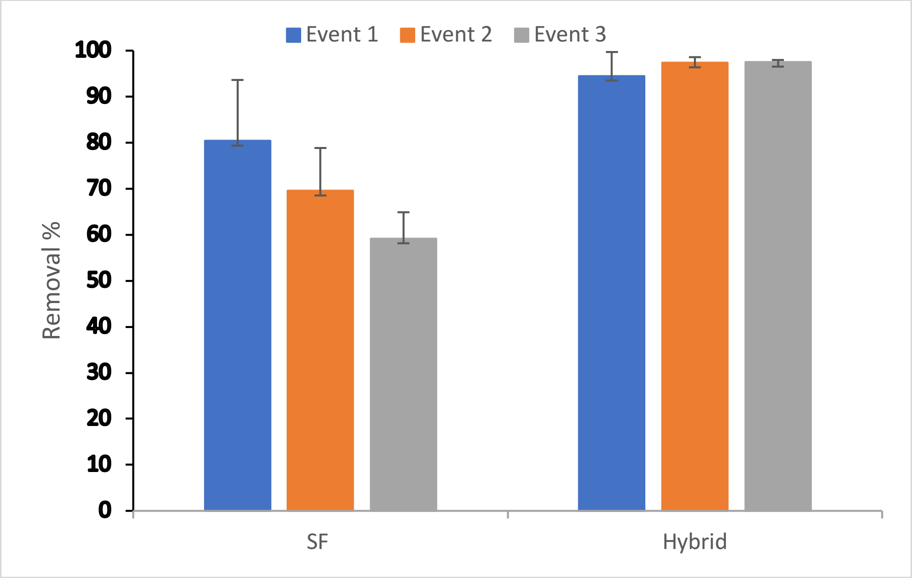

Fig. 7 Comparison of removal efficiencies from each pulse event. The first event saw a greater removal efficiency of glyphosate in the SFW compared to the latter two events. Removal efficiency of glyphosate began to decrease over time in the SFW during the second and third pulse events. For the hybrid constructed wetlands, removal efficiencies remain greater than that of the SFW and even increase with each pulse event.

During the first pulse event, surface flow concentrations of glyphosate decreased from 5.0 ppm to 3.0 ppm. In the second pulse event, concentrations decreased from 5.4 ppm to 2.5 ppm. In the final pulse event of the study, glyphosate concentration decreased from 4.5 ppm to 3.3 ppm. The overall removal rates of the surface wetland for the three pulse events were 80%, 69%, and 59% respectively (Figure 7). Meanwhile, the hybrid wetlands had relatively stable removal rates for three pulse events, which were 94%, 97%, and 97% respectively.

Glyphosate is a highly water-soluble chemical with a water solubility of 5 to 10 mg/mL at 17.8 ºC (NTP, 1992). The constructed wetlands in this experiment showed efficient removal of glyphosate in contaminated water. Compared to primary surface flow wetlands, combined systems increased the rate of removal. Biophysiochemical processes involving water, soil, plants, and microorganisms have been attributed to the remediation of contaminated waters. Bioremediation through plant uptake and microbial degradation play very important roles in the removal of organophosphorus pesticides including glyphosate (Liu et al. 2019). Soil matrices provide sites needed for the growth of biofilms and establishment of rhizospheres to which pesticides can be absorbed and absorbed into these sites (Rogers and Stringfellow, 2009). In subsurface flow constructed wetlands, bacteria and fungi in soil and rhizospheres, mineralize and transform pesticides through two pathways: specific enzymatic and nonspecific enzymatic reactions (Liu et al. 2019).

Organophosphate pesticides have been studied widely for its removal in constructed wetlands however, most literature show the removal for either surface flow or subsurface flow constructed wetlands rather than hybrid constructed wetlands, as used in this experiment. A field study using vineyard runoff was conducted using a subsurface horizontal flow constructed wetland with a retention time of 10.8 hours (Maillard et al. 2011). The experiment was conducted in the spring and summer with removal efficiencies being 90% and 77%, respectively. The hybrid wetlands in this experiment utilized horizontal flow constructed wetlands and were able to achieve higher removal efficiencies.

A study comparing two subsurface flow wetlands showed the removal rate of glyphosate in the wetlands to be 90.3% and 66.4% respectively (Liang et al. 2020). The wetlands were both planted with common reeds, however substrate differed; one being pyrrhotite and the other being limestone. Though removal rates were high, it was still lower than the removal by the hybrid systems used in this experiment (≥98% removal). Cattails and bulrush planted in the subsurface flow wetlands contributed to the phytoremediation of the simulated wastewater. Evidence of this was shown as water samples from the outflow collection point of the subsurface flow wetlands showed glyphosate concentrations below the limit of detection. Cattail and bulrush plants have been used widely in many different constructed wetland studies. One study which looked at the removal of the pesticide tebuconazole observed removal efficiencies reach up to 99.8% in wetland mesocosms planted with *Juncus effusus* (common rush), *Typha latifolia* (Broadleaf Cattail), *Berula erecta* (Water Parsnip), *Phragmites australis* (Common Reed) and *Iris pseudacorus* (Yellow Iris) (Lyu et al. 2018). Passive diffusion is how most herbicides can move across plant membranes making this an important process for the absorption of wetland vegetation. Concerning glyphosate, a previous study had shown significantly high absorption in native cattail (*Typha latifolia*) rhizomes (Zheng et al. 2017).

The substrate used in this experiment played an important role in the removal of glyphosate from the effluent. Soil media in constructed wetlands act as a support matrix, providing favorable conditions for microorganisms and biofilm renewal (Wu et al. 2017). Substrate can also directly influence adsorption processes through substrate surface adsorption and migration and diffusion into the internal matrix (Singh and Walker 2006). Important parameters that are desired in the substrate used in constructed wetlands are high sorption capacity and wide availability, reasonable price, high hydraulic conductivity, favorable to biotic components, and longevity (Liu et al. 2019). Sorption of pesticides on the substrate surface is complex involving many different processes including hydrophobic partitioning, van der Waals interaction, electrostatic interaction, ion exchange, surface complexation, and hydrogen bonding (Rogers and Stringfellow, 2009; Dordio and Carvalho 2013; Li et al. 2014; Tolls, 2001). Liu et al. 2019 observed that some organophosphorus pesticides (i.e., diazinon, chlorpyrifos, parathion, etc.) that are immobile or have limited mobility tightly adsorb and precipitate on substrate surfaces. Other physiochemical properties of substrate that can affect the adsorption of organophosphorus pesticides include particle size, porosity, volume weight, specific surface area, moisture, adsorption sites, mineral content, surface charge, exchangeable ions, cation exchange capacity, organic matter content, and competitiveness with phosphate (Erban et al. 2018; Gimsing and Borggaard, 2007; Maqueda et al. 2017; Gimsing et al. 2007, Nguyen et al. 2018; Vagi et al. 2010; Alfonso et al. 2017; Gebremariam et al. 2012; Pessagno et al. 2008; Rotich et al. 2004; Huntscha et al. 2018; Jonge et al. 2001; Ortiz et al. 2017). Chemical properties of substrate, matter more concerning adsorption of organophosphorus pesticides. A study showed high glyphosate affinity in soils had been associated with clay, CEC, aluminum, iron, and a low pH and phosphorus content (Guijarro et al. 2018).

Conclusions

This study utilized mesocosms to study removal of glyphosate for three pulsed events by surface wetland alone and hybrid wetlands consisting of combination of surface flow and subsurface flow systems. The average removal efficiency of surface flow wetlands was 69.3% compared to 96% of hybrid flow wetlands. The removal efficiency of surface flow wetlands depleted over time for each pulse event unlike that of hybrid systems. For each of the three pulse events, the surface flow constructed wetlands obtained overall removal of 79%, 69%, and 59%. However, the removal rates of the hybrid systems were 94%, 97% and 97% for corresponding pulse event. Therefore, hybrid wetlands, surface flow wetlands coupled with subsurface flow wetlands, removed glyphosate at a higher percentage compared to only using a surface flow wetland. Consequently, establishing or adding a hybrid flow component to existing wetlands may achieve higher removal of agrochemicals, like glyphosate. Through a controlled small-scale study, this experiment showed the potential of agrochemical, namely pesticides, remediation by hybrid constructed wetlands to be used in real world settings such as agricultural areas. This experiment supported the notion that hybrid wetlands, a low-cost nature based passive treatment solution, can help keep our waters safe and clean.

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