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Environmental Pollution Control

RECYCLED GREEN ROOF MEDIA AND ITS EFFECT ON WATER QUALITY

A Thesis in

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by

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ABSTRACT

Green roofing is listed as one of the best management practices (BMP) for the control of stormwater quantity (DEP, 2006). Green roofs can capture and retain rainwater, decrease the peak rate of runoff from roofs, and delay the runoff peak. In addition to quantity control, green roofs also may provide water-quality benefits. The focus of this research was the potential use of green roofs containing recycled materials as a pre-treatment device prior to rainwater harvesting for non-potable use. This project evaluated three recycled materials, crumb rubber, compost and biosolids, for their potential use in green roof media as complete or partial replacements for the current inorganic and organic components of green roof media. To be a viable green roof component the media must maintain or increase rainwater pollutant retention, compared to commercially-available green roof media, while not releasing problematic pollutants such as additional nutrients or heavy metals, e.g. the water collected afterwards would be safe enough for re-use in non-drinkable applications and/or discharge. In addition, the media must not have a substantial impact on plant growth. Two runs were performed, one without adding an *E. coli* spike on day two and one with the spike, to determine the impact of increased biological activity on pollutant retention in both commercial and recycled-component media. Both synthetic stormwater and the resultant effluent were collected from each media combination and were analyzed for the following parameters: Total Nitrogen, Total Phosphate, Chemical Oxygen Demand (COD), Nitrate, Ammonia, and Dissolved Copper. After analysis, the bacteria appeared to decrease or prevent an increase in concentration the following parameters: Nitrate, Total Nitrogen, and COD. In general, mixtures with the compost appeared to meet water quality guidelines, although decreasing the organic content to a level that the plants need, but no more, should further reduce any nutrient leaching.

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INTRODUCTION:

The United States has seen a steady increase in population over the past century. According to the U.S. Census Bureau, the U.S. population (as of July 2010) consists of more than 308 million people (U.S. Census Bureau, 2010). One of the issues that come with an increasing population is, finding ways to support an ever-growing population.

With the increase in developed land for the growing population, the amount of pervious land, that allows water infiltration, thus is reduced. Areas with pervious land are beneficial to people because when water is infiltrated into the soil, it can help replenish aquifers and wells in nearby areas. In areas where pervious land is minimal and/or where water costs are high, other solutions to the potential water shortage are needed.

A solution that could remedy this problem is rainwater harvesting. In Nicholson's (2009) paper, on rainwater harvesting for non-potable reuse, it states "Reclaimed water, or greywater, can be utilized in many household applications where potable water is traditionally used. Some such applications include the following: toilet flushing, car washing, laundry, and the watering of plant and gardens". Using reclaimed water for non-potable uses would reduce the amount of potable (drinking) water used and would thus become readily available for other purposes.

In this research, green roofs as potential pre-treatment devices prior to rainwater harvesting was the main focus. According to an article written by Clark, et al. on rainwater harvesting:

> Roofs are an ideal location for rainwater for three main reasons. First, gravity can be used to collect runoff thus eliminating the need for electricity for pumps. Second, when

> compared to toilet and other household wastewater, water collected from roofs could be relatively clean. Third, a second and separate plumbing system would not be required. (Clark, 2007).

There are two types of green roofs: extensive and intensive. The two types of green roofs are differentiated by their cost, depth of growing medium and choice of plants (Peck and Kuhn, 2011). Extensive green roofs provide many of the same environmental benefits as intensive green roofs but are also designed to be low maintenance and not for public use while intensive green roofs are designed to be used by the general public (EPA, 2008).

This research focused on extensive green roofing. Extensive green roofs' growing media depths typically are between 2 to 6 inches. Because of their shallow depth and the harsh environmental conditions for plants, green roofs usually have a low diversity of plants (typically sedums, grass and moss) that can survive in extreme weather conditions, high winds, and drought.

Within the past few decades, green roof use in the U.S. has increased. Green roofing has been established as one of the best management practices (BMP) for stormwater control (DEP, 2006). Green roofs can capture and retain rainwater, decrease the peak rate of runoff from roofs, and delay the runoff peak. Also, extensive green roofs require limited maintenance once they are constructed and the plants established.

This research focused on the potential to replace current inorganic (expanded shale) and organic (peat) components of extensive green roof media with recycled products, including crumb rubber, compost, and biosolids. These components were evaluated in laboratory column tests for their ability to remove and retain nutrients and copper from synthetic stormwater without adding pollutants to the stormwater, with the results compared to water quality criteria and to the results from other studies on green roof media water quality.

Media Components: Crumb Rubber

Crumb rubber is a popular medium for various applications such as synthetic turf, athletic surfaces, modified asphalt pavement, and playground safety material. However, one drawback to the use of crumb rubber has been the leaching of heavy metals such as copper and zinc (Edeskar, 2004; Kallvist, 2005). This leaching could prevent the use of crumb rubber in green roof, and potentially in other stormwater runoff, media. Studies have shown that pH levels of the water greatly affects the heavy metal load that leaches out of crumb rubber, but the resulting amounts may not be large enough to have a very negative effect on the overall quality of water filtered through a green roof media. Results from a study on environmental properties of tire shreds showed the leaching ability of zinc was relatively high, at neutral pH-conditions, while copper occurred in low levels (Edeskar, 2004). The study also determined that, since the total amount of copper in the rubber tires were low, the copper leachate would not be a problem.

Depending on the composition of the remaining green roof media components, some buffering capacity of the stormwater may exist and may prevent the leaching of these heavy metals. Long (2007) showed that a green roof media composed of expanded shale and an organic component was able to buffer acidic rainfall. Long states "lab studies showed that the green roof media was able to buffer pH to near-neutral or above-neutral values" (Long, 2007). In a field-based green roof study, tests showed "green roof media can buffer acid precipitation for approximately 10 years", but afterwards modifications must be done to maintain buffering capacity (Berghage, 2009).

In 2005, the Norwegian Pollution Control Authority released a risk assessment on artificial turf systems, which incorporates crumb rubber, that states that zinc is the component that poses the biggest environmental risk because it had the highest leachate concentration (with 3,290 µg/l) from an artificial turf pitch (area of $7200m^2$ and 800mm precipitation) over one year. However, the same Norwegian risk assessment states that “the total quantities of hazardous substances which are leached from an artificial turf pitch are however modest, so that any environmental effects will only be localized” (Kallqvist, 2005). Nicholson (2009) showed that even though pollutants released from discharged runoff (from various roofing materials, not solely green roofs) could be harmful to local wildlife and plants, it was determined that “most increased pollutants would not be harmful for greywater uses such as car washing and watering lawns”, especially for green roofs, which had much lower pollutant discharges than the uncoated, galvanized zinc.

The belief that there are heavy metals leaching from crumb rubber has almost been universally accepted; the argument that has been ongoing is whether the heavy metal concentrations leaching from crumb rubber are significant enough to be hazardous to the environment and to humans and animals.

Media Components: Compost

In addition to the crumb rubber, compost was another recycled component evaluated for its potential to be added to green roof media as the organic matter source. According to the Environmental Protection Agency, “compost is organic material that can be used as a soil amendment or as a medium to grow plants… It is created by combining organic wastes (e.g., yard trimmings, good wastes, manures) in proper ratios into piles, rows, or vessels; adding bulking agents (e.g., wood chips) as necessary to accelerate the breakdown of organic materials;

and allowing the finished material to fully stabilize and mature through a curing process" (EPA, 2011).

Clark's thesis about the evaluation of filtration media for stormwater runoff treatment, states that "composts have been found to have a very high capacity for adsorbing heavy metals, oils, greases, nutrients, and organic toxins due to the humic content of the compost…They… remove the toxicants from the runoff either by adsorption or ion-exchange" (Clark, 1996). Compost was selected because it can provide the natural organic matter and nutrients that green roof pants would need to survive, plus it may be able to capture and retain any metals released by the crumb rubber.

Media Components: Biosolids

The third media component evaluated was biosolids. According to the Environmental Protection Agency, biosolids are "nutrient-rich organic materials that resulted from treatment of sewage sludge (semisolid or liquid untreated residue generated during the treatment of domestic sewage in a treatment facility). When treated and processed, sewage sludge becomes biosolids which can be recycled and applied as fertilizer to sustainably improve and maintain productive soils and stimulate plant growth" (EPA, 2012).

The biosolids used for the experiment were collected from the Joint Municipal Authority of Wyomissing Valley and characteristics consisted of 5.03% TN (Total Nitrogen) and 4.79% P_2O_5. They were heat-dried, using indirect heat from a biosolids dryer system to evaporate water from the wastewater solids. The heat drying process was conducted to destroy the pathogens and eliminate most water from the biosolids. The biosolids were classified as Class A, which means, theoretically, they should be pathogen free.

Water Quality Criteria

In order to determine whether the leachate nutrient concentrations would be at an acceptable level for harvesting, they must be compared to other research results and to approved criteria concentrations (Table 1). The aquatic and human health (drinking water and surface water as, lakes and reservoirs, and rivers and streams) water quality criteria (WQC) were developed by the EPA in order to establish "quantified endpoints" that would provide sufficient protection to maintain downstream uses. The WQC did not address nitrate specifically, so the NO_2+NO_3 was used in its place.

In addition to the WQC, the results of this project also can be compared to results reported by other researchers. Moran's paper, focusing on the use of extensive green roofs in North Carolina, indicated higher concentrations of Total Nitrogen and Phosphorus were present in greenroof runoff than in the control roof runoff (Moran, 2004). Teemusk and Mander reported on the runoff water quality of a lightweight aggregates-based green roof through short term events such as rainfall, snow melt, etc (Teemusk and Mander, 2007). The two different results included from their paper are from different outflows; they are also taken from the "moderate" runoff section. The third study included in Table 1 focused on nutrient runoff, substrate nutrient storage and plant uptake while using combinations of fertilizers and vegetation (Emilsson, 2006). The use of fertilizers likely increased the nutrient concentrations in the runoff, resulting in substantially higher concentrations than seen in the other two studies.

Table 1. Nutrient Limit Criteria List (all concentrations in mg/L)

	Ammonia	Nitrate Or NO_2+NO_3*	Total Nitrogen	Total Phosphorus	Chemical Oxygen Demand (COD)	Copper (Dissolved)
Human Health Criteria	N/A	10	N/A	N/A	N/A	1.3
Lakes and Reservoirs Water Quality Criteria	N/A	0.017-0.668*	0.205-2.405	0.0073-0.0804	N/A	N/A
Rivers and Streams Water Quality Criteria	N/A	0.003-5.96*	0.092-6.363	0-1.3879	N/A	N/A
Moran, A., et. al. (2004)	N/A	N/A	~0.8-6.9	N/A	N/A	N/A
Teemusk, A., et. al. (2007)	0.33, 0.28	0.7, 0.8	2.1, 1.9	0.036, 0.026	37, 26	N/A
Emilsson, T., et. al. (2006)	0.0575	33.11	33.02	0.479	N/A	N/A

OBJECTIVE:

The project objective was to determine in laboratory-scale column studies the pollutant removal and/or leaching potential of both traditional green roof components (expanded shale and peat moss sold as a commercial media) and recycled materials (crumb rubber, compost, and biosolids) proposed as replacements for traditional components. The second objective was to determine the influence of an active microbial population on the leaching potential of nutrients from proposed green roof media mixes and whether microbial uptake could reduce substantially the drawback of most green roof media - the leaching of nutrients during plant establishment and possibly longer. The results from these tests were compared to recreational water quality standards and drinking water standards to determine whether the water was acceptable for harvesting after passing through the green roof media. The results also were compared to the results of other green roof studies to determine whether a media made from part or all recycled components can provide water quality equivalent to that provided by commercial and research-reported media mixes.

MATERIALS & METHODOLOGY:

Experimental Setup:

This project is part of a larger study on the potential of replacing, conventional green roof media with recycled materials. The overall study focused on optimizing a media mix that incorporated, at least partially, these recycled materials, yet still met the requirements for green roof media in terms of its physical and hydraulic characteristics. The research was investigating the following characteristics of green roof media: (1) the structural, physical, chemical, and microbiological characteristics of both the medium and of leachate/runoff associated with the medium and (2) the ability of the medium to support plant growth. This thesis focuses on the water quality chemistry from these studies.

Table 2. Analyte List for Testing

Analyte	Analytical Method
Total Nitrogen	Std Methods (S.M.) 4500-N, C
Total Phosphate	S.M. 4500-P B
COD	S.M. 5220-COD C
Nitrate	S.M. 4500-NO_3 D
Ammonia	S.M. 4500-NH_3 Nitrogen, C
Copper, dissolved	S.M. 3500-Cu, B

Green Roof Component Preparation:

For this study the following potential media components were used: two composts (Laurel Valley and Recycled Ag), Class A biosolids from the Joint Municipal Authority of Wyomissing Valley, and two crumb rubber supplies (Liberty Tire and VS crumb rubber), and a commercial green roof media from Suntech. All of these components, except for the commercial green roof media, were sieved through a 2mm sieve before use. Table 3 provides a key to the abbreviations used to designate each component.

Table 3. Key to Component Names

Component Name	Key
Laurel Valley compost	LV
Recycled Ag compost	AG
Class A biosolids	BS
Liberty Tire crumb rubber	LT
VS crumb rubber	VS
Peat	Peat
Expanded Shale	ES
Suntech commercial green roof media	Suntech Media

Experimental Setup- Synthetic Rainwater:

For these experiments, synthetic rainwater that had been designed to reflect the typical mid-Atlantic region rainfall composition was used. The synthetic rainwater included 23 μM of sodium chloride (NaCl), 18 μM of sulfuric acid (H_2SO_4), and 18 μM of nitric acid (HNO_3) for every 100mL of water. The synthetic rainwater pH was also in the range of 4.2-4.4(Davis and Burns 1999).

Experimental Design- Column Studies

Twelve plexiglass columns were constructed using the media as described in Table 4. Each column was filled with media to a depth of 4 inches. Once the columns were filled to the 4 inch line they were tapped 3 times to pack the media and new media added to the top, if necessary, to ensure a total depth of 4 inches. The Suntech (commercial) media was used as supplied by the manufacturer. For the columns containing recycled components, the columns were constructed with a mixture of 15% of an organic component and 85% was an inorganic component by volume. While all columns were watered according to the schedule described below, analytical costs prevented analyses of all leachate. Water quality samples were collected from only one column of each media type.

Table 4. Green Roof Media Mixes Column Study

Column Number	Organic Component	Inorganic Component
1	SunTech Media	
2	SunTech Media	
3	SunTech Media	
4	LV	LT
5	LV	LT
6	LV	LT
7	AG	LT
8	AG	LT
9	AG	LT
10	BS	LT
11	BS	LT
12	BS	LT

Two sets of experiments were run with the columns rebuilt between each run. The first run used spiked stormwater as described above. The second run used the same spiked stormwater but spiked with *E. coli*. The *E. coli* spike occurred on Day 2 of the second run. The leachate from unspiked columns were collected from 11/1/11 to 11/21/11 while spiked columns between

12/19/11 to 1/5/12. This timing was important in interpreting the results because the organic components were obtained once in October 2011 and aged in the laboratory before they were used in the column. The spiked rainwater contained approximately 316 CFU/mL yielding approximately 3.16 x 10^4 CFU in the 200mL of rainwater.

The columns were watered approximately two times a week for three weeks using a total of 200 mL of synthetic rainwater per column per watering event. The leachate was collected for chemical analysis. The leachate was collected by sterile glass beakers from each of the columns. Columns were allowed to drip for 2-5 min before the leachate was removed for analysis. The leachate was analyzed for the constituents from Table 2.

RESULTS:

Ammonia:

The figures show the ammonia results, for the different media, comparing columns with and without a spike of *E. coli* on day 2 (Figure 1, commercial green roof media; Figure 2, AgriCompost and crumb rubber, and Figure 3, biosolids and crumb rubber). The initial ammonia concentrations in the leachate are very small in the crumb rubber-compost and commercial media mixes. They also are comparable between the spiked and unspiked runs. However, the crumb rubber-biosolids are different from the compost and commercial media mixes in two ways: (1) the initial ammonia concentrations were substantially different between the spiked and unspiked runs, likely due to aging of the biosolids during storage before the spiked runs (the spiked runs started a month after the unspiked runs ended), and (2) the initial ammonia concentrations in the biosolids for both the spiked and unspiked runs were substantially greater compared to the commercial and compost mixes.

Another possible reason for the substantial difference in initial leachate concentrations between the crumb rubber-biosolids mix and the other two media could be due to the heat-drying process of the biosolids. Not only did the heat-drying process remove pathogens and water, it also killed the microbes within the biosolids and may have changed the chemical structure of the media. This process resulted in a media that, until microbes were added and established, did not stabilize and left nutrients available for transport with the water.

For the commercial green roof media (Figure 1), the unspiked columns steadily decreased over time. The steep decrease in the first week of the experimental run could be due to a flushout of loosely-bound nutrients. The spiked column decreased on day 2 (the day where the *E. coli* was added to the column), then increased and then fluctuated until the end of the experimental run. The decrease on day 2 may be an anomaly and not due to the introduction of the bacteria in the column. Since replicates were not analyzed, further investigation would be needed to confirm whether the trends seen here are a result of the spike.

For the AgriCompost and Liberty Tire column (Figure 2), both the spiked and un-spiked data appear to follow a similar overall trend of relatively steady effluent concentrations. The big increase for the un-spiked column could either be an anomaly or a delayed flushing out from the media. For the Biosolids and Liberty Tire (Figure 3), the spiked column decreases after the introduction of *E. coli* and then flattens out for the rest of the experiment. The un-spiked column steadily increases over time. This indicates that there is an impact of creating an active microbiological population in the column, especially when using an organic medium that is not chemically stable. As noted above for the initial effluent concentrations, the biosolids did not stabilize over time with storage because the microbial population has been substantially weakened, plus the process appeared to convert the nutrients from organically bound nutrients to easily flushed out inorganic ones. The addition of the bacteria would be expected to have a substantial impact because they can use these available nutrients for population growth. This effect was not seen in the commercial media or the compost, likely because the media were aged and relatively stable in terms of potential ammonia release.

When comparing the ammonia leachate concentration results with the respective values listed in Table 1, the commercial and compost-crumb rubber media mixes are both lower than the literature. However, the biosolids-crumb rubber media mix was significantly higher.

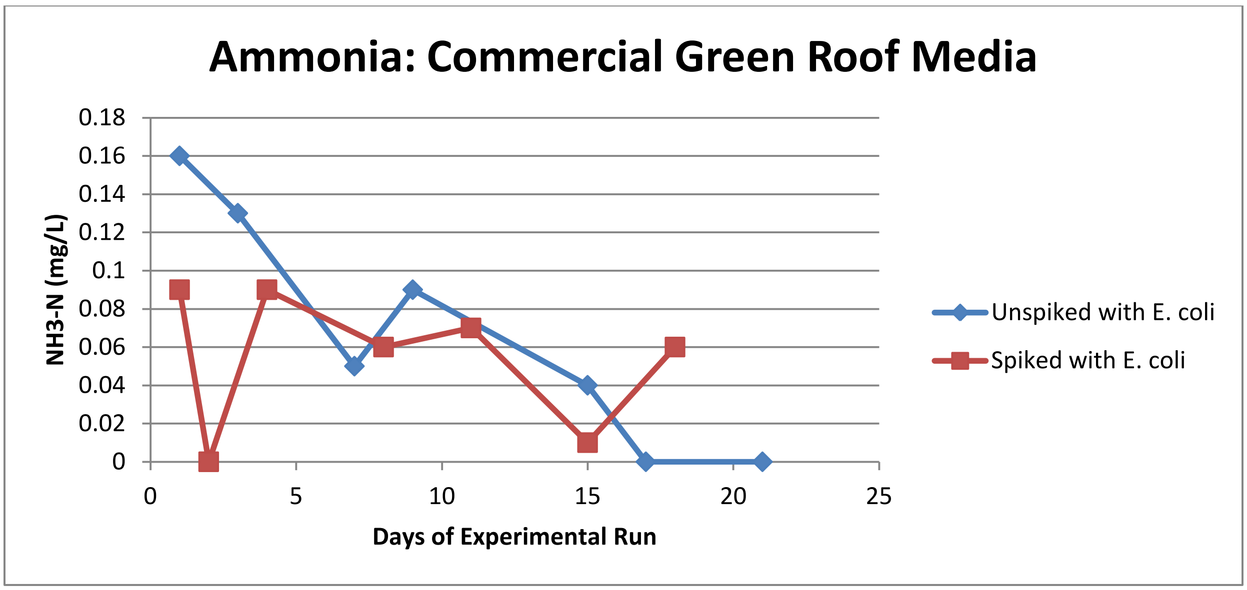

Figure 1. Comparison of spiked/non-spiked columns for Ammonia in Commercial Green Roof Media

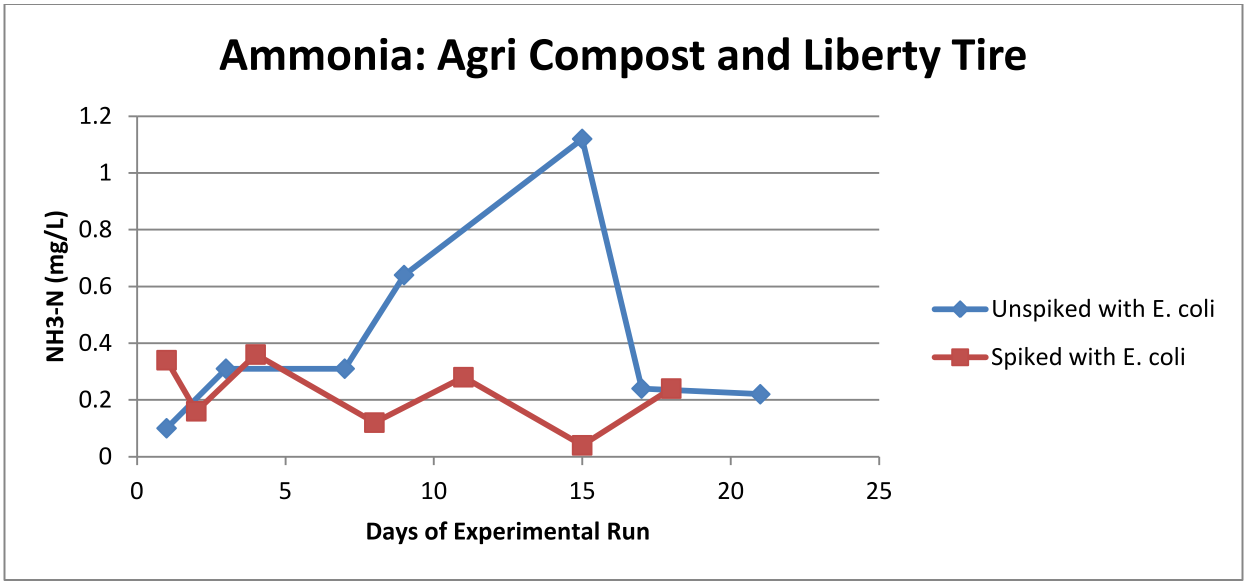

Figure 2 Comparison of spiked/non-spiked columns for Ammonia in AgriCompost and Liberty Tire

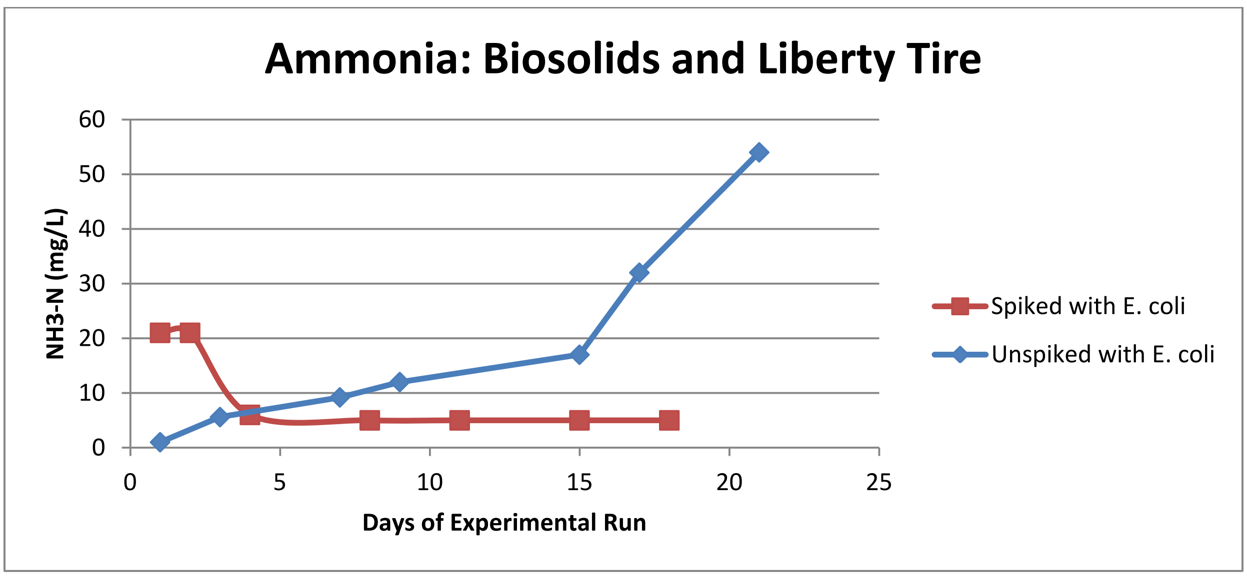

Figure 3 Comparison of spiked/non-spiked columns for Ammonia in Biosolids and Liberty Tire

Nitrate:

The three figures show the nitrate results comparing columns with and without a spike of *E. coli* on day 2 (Figure 4, commercial green roof media; Figure 5, AgriCompost and crumb rubber, and Figure 6, biosolids and crumb rubber). The initial nitrate concentrations in the leachate were very small in the crumb-rubber-compost and biosolids mixes compared to the commercial media mix, which was substantially greater. However, all three media mixes are comparable between the spiked and unspiked runs.

For the commercial green roof media (Figure 4), the unspiked columns increased by day 3 then continually decreased and steadied out until the end of the experimental run, with the decrease being a result of the early washing out of loosely-bound nutrients from the media. The spiked column declined on day 2, after the addition of *E. coli*, and then held relatively steady for the remainder of the experimental run.

For the AgriCompost and Liberty Tire (Figure 5), the spiked decreased slightly on day 2 and remained steady for the remainder of the experiment. The un-spiked column was variable throughout the experimental run. The steady decrease and leveling off in the spiked column indicates the beneficial impacts on effluent quality of an active microbial population, for the same reasons described for ammonia. For the Biosolids and Liberty Tire (Figure 6), the unspiked column effluent may be slowly increasing in time, although the results are highly variable. This may be due to the washing out of loosely bound nitrate. For the spike column, the effluent remained relatively steady throughout the experimental run.

When comparing the nitrate leachate concentrations to the literature from Table 1, all three media (commercial, compost, biosolids) were higher than the literature, but only the commercial media was higher than drinking water quality standard (the Maximum Contaminant Level is 10 mg/L as N) for treatment before reuse. The results show that establishing a microbial population reduces nitrate discharge.

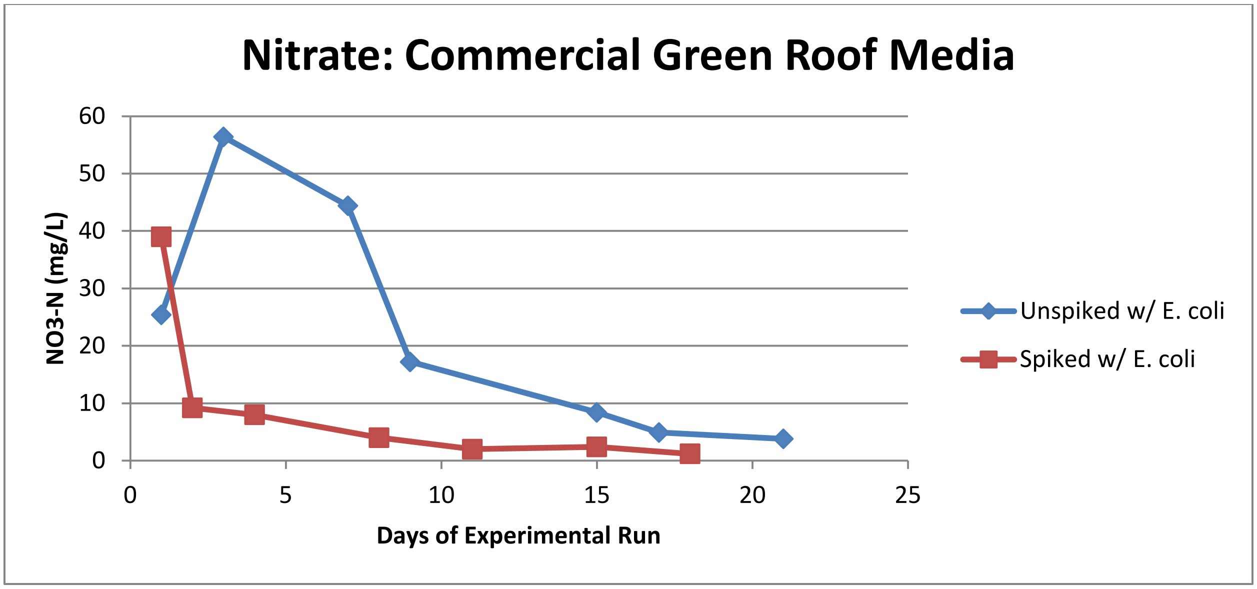

Figure 4 Comparison of spiked/non-spiked columns for Nitrate in Commercial Green Roof Media

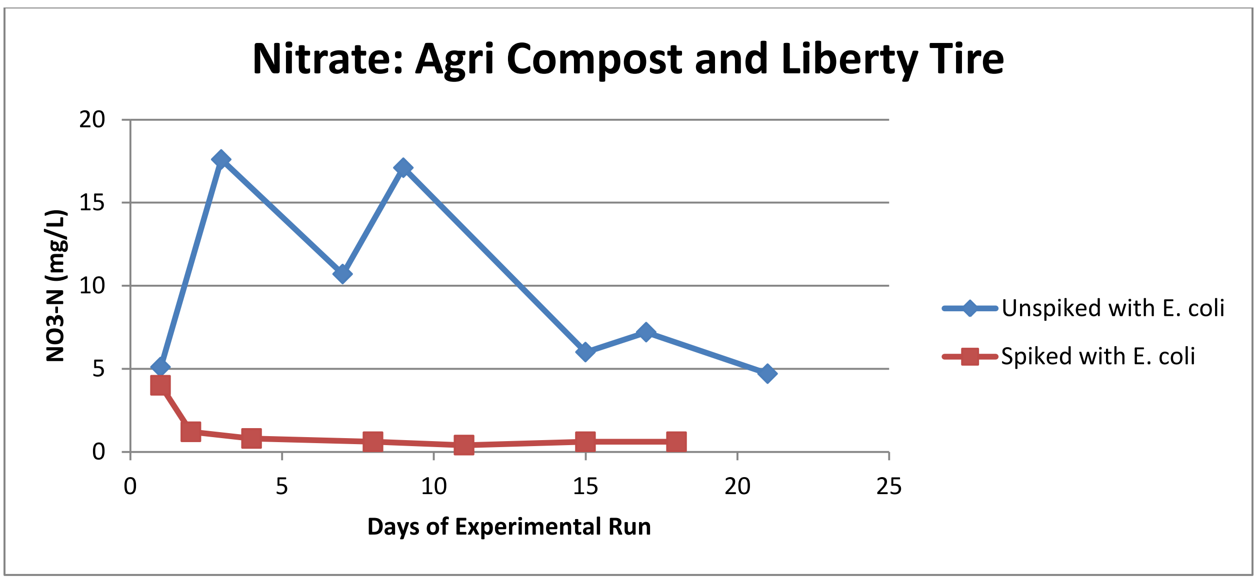

Figure 5 Comparison of spiked/non-spiked columns for Nitrate in AgriCompost and Liberty Tire

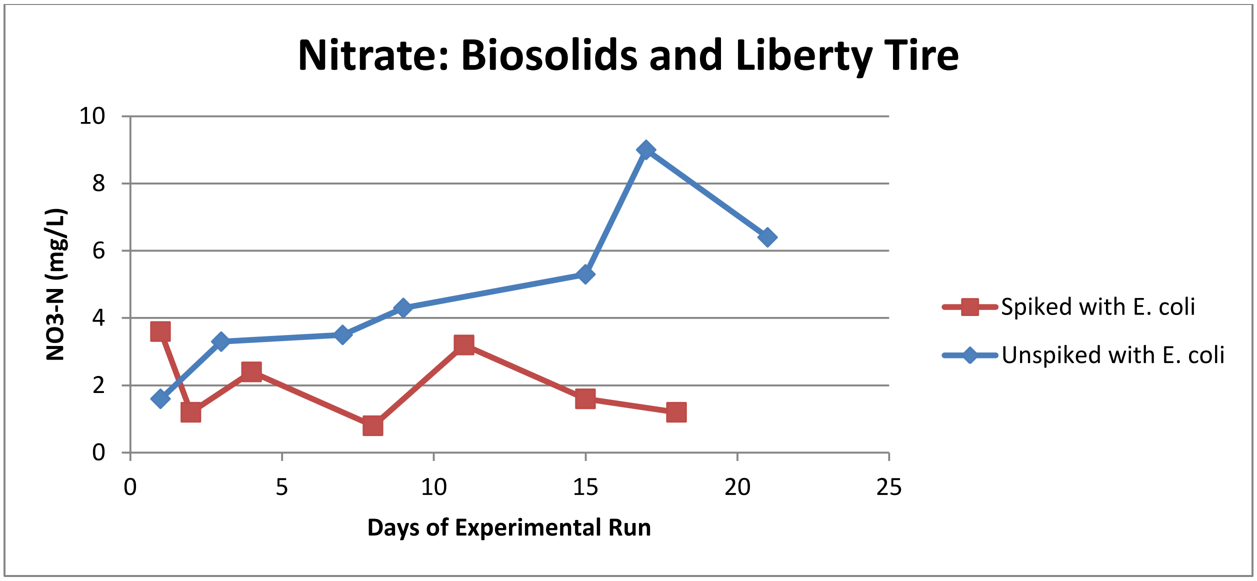

Figure 6 Comparison of spiked/non-spiked columns for Nitrate in Biosolids and Liberty Tire

Total Nitrogen:

The three figures show the total nitrogen results for the three media comparing the columns with and without a spike of *E. coli* on day 2 (Figure 7, commercial green roof media; Figure 8, AgriCompost and crumb rubber, and Figure 9, biosolids and crumb rubber). The initial total nitrogen concentrations in the leachate in the three media are substantially different from one another (with the crumb rubber-biosolids having the largest initial range, followed by the commercial media and then the AgriCompost mix). There are also substantially different initial total nitrogen concentrations between the spiked and unspiked runs for each three media mixes as well, with the crumb rubber-biosolids mix leachate having almost a 200mg/L difference in Total Nitrogen. Once again, it is believed that the difference in initial values could be due to the aging of the media

For the commercial green roof media (Figure 7), both the spiked and un-spiked columns have a similar trend (they steadily decreased and then steadied out). It did not appear that *E. coli* had an effect on the total nitrogen in the column. For the AgriCompost and Liberty Tire (Figure 8), the un-spiked column fluctuated throughout the experimental run, while the spiked column steadily decreased once *E. coli* was introduced into the media. For the biosolids and Liberty Tire (Figure 9), the un-spiked column leachate was highly variable, while the spiked column had a decrease and leveled out over time once *E. coli* was introduced into the media.

When comparing the total nitrogen leachate concentration results with the respective values listed in Table 1, compost and biosolid-crumb rubber media mixes are higher than the literature. For the commercial media, the unspiked column was significantly higher than the literature, while the spiked column gradually decreased and stabilized at concentrations close to the literature in Table 1.

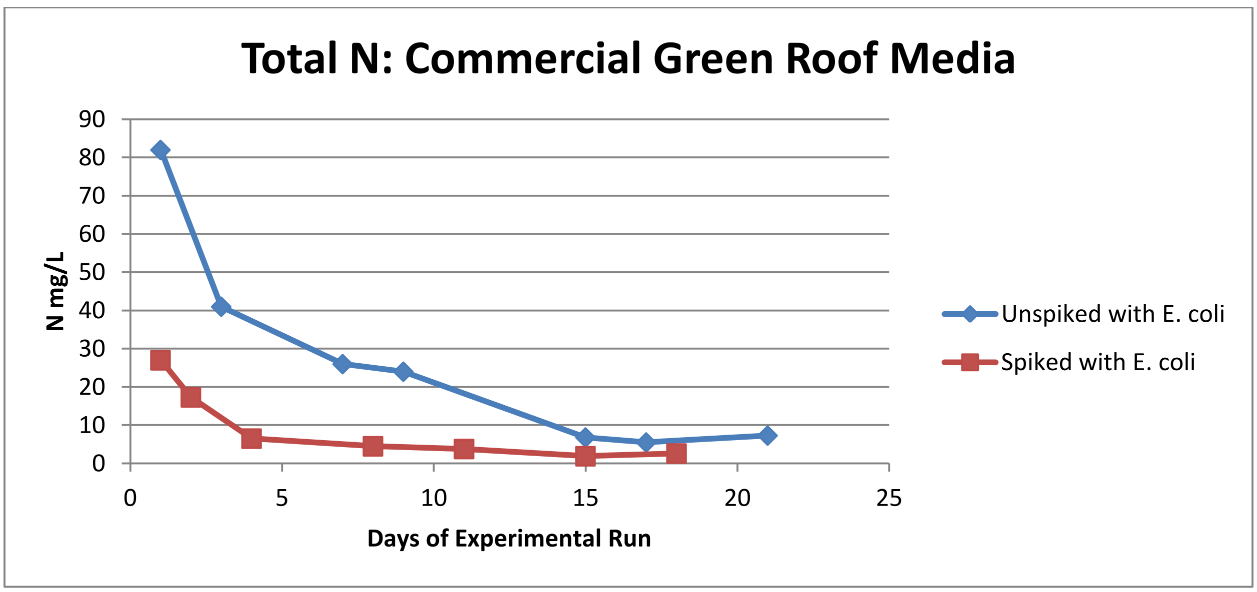

Figure 7 Comparison of spiked/non-spiked columns for Total Nitrogen in Commercial Green Roof Media

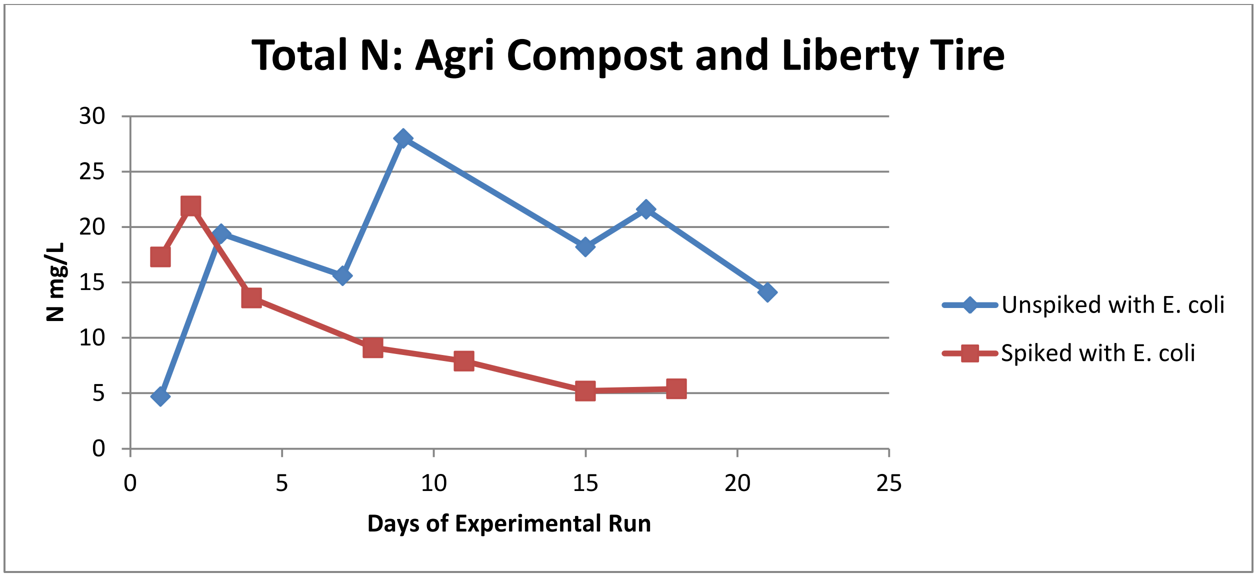

Figure 8 Comparison of spiked/non-spiked columns for Total Nitrogen in AgriCompost and Liberty Tire

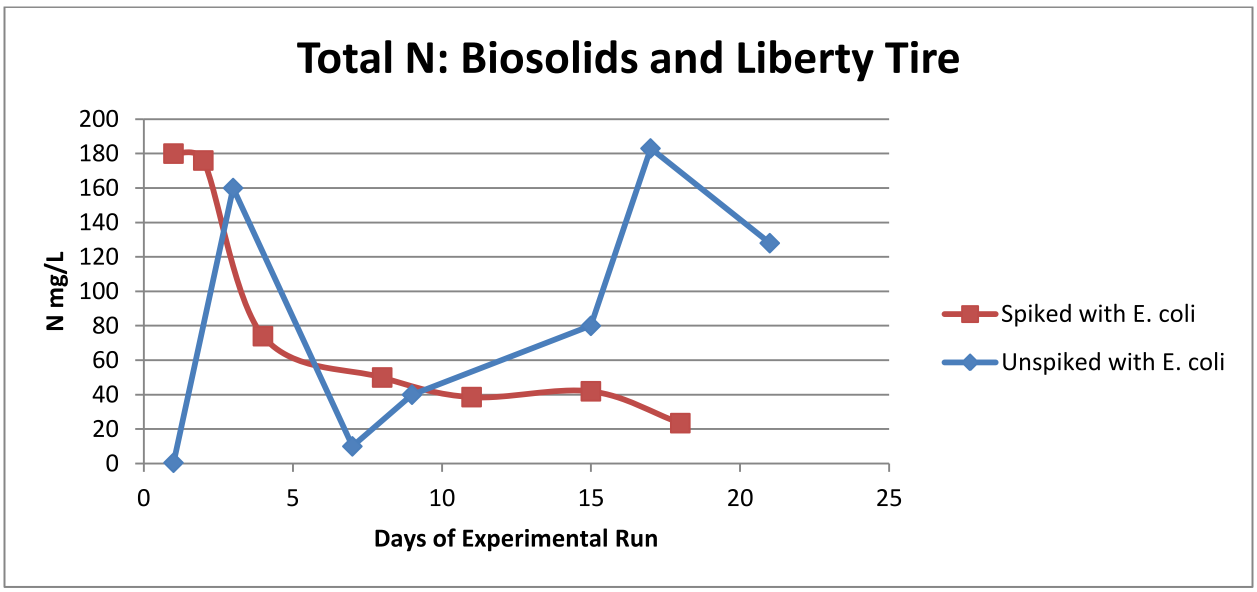

Figure 9 Comparison of spiked/non-spiked columns for Total Nitrogen in Biosolids and Liberty Tire

Total Phosphorus:

The three figures show the total phosphorus results for the three media comparing columns with and without a spike of *E. coli* on day 2 (Figure 10, commercial green roof media; Figure 11, AgriCompost and crumb rubber, and Figure 12, biosolids and crumb rubber). The initial Total Phosphorus concentrations in the leachate are small in the crumb rubber-compost and commercial media mixes, compared to the slightly larger concentration of the biosolid mix. However, when looking at the initial concentrations between the spiked and unspiked runs, only the crumb rubber-compost was similar while the crumb rubber-biosolids and commercial media mixes were substantially different.

For the commercial green roof media (Figure 10), both the spiked and un-spiked columns had a similar effluent concentration after approximately day 7. However, the initial results were vastly different. The unspiked column started with a high initial concentration that decreased slightly before leveling off to a final concentration of approximately 6 to 7 mg/L. For the spiked column, the initial concentration was approximately 1 mg/L, but rose to approximately 6-7 mg/L after 5 days. This increase indicated that loosely-bound or dissolved phosphorus took several days to be washed out of the media. For the AgriCompost and Liberty Tire (Figure 11), the spiked and un-spiked columns are very similar, throughout the entire experimental run. For the biosolids and Liberty Tire (Figure 12), the initial concentrations in the spiked column were larger than in the unspiked column, potentially as a result of aging of the media. For the unspiked column effluent, there may be an increase in the effluent concentration over time, which is opposite than what is seen in the spiked column effluent. Since replicates were not analyzed and since the unspiked results are highly variable, additional testing would be needed to confirm whether the increase with time is a trend or an aberration.

When comparing the total phosphorus leachate concentration results with the respective values listed in Table 1, all three media (commercial, compost, and biosolids mixes) were higher than water quality criteria and most green roof water quality studies.

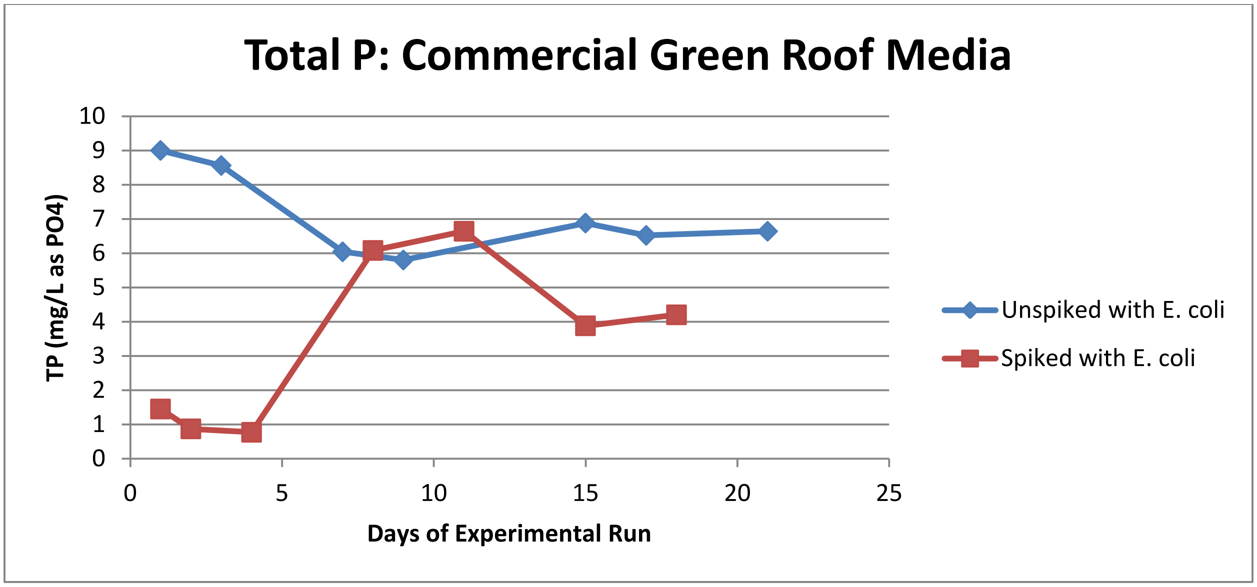

Figure 10 Comparison of spiked/non-spiked columns for Total Phosphorus in Commercial Green Roof Media

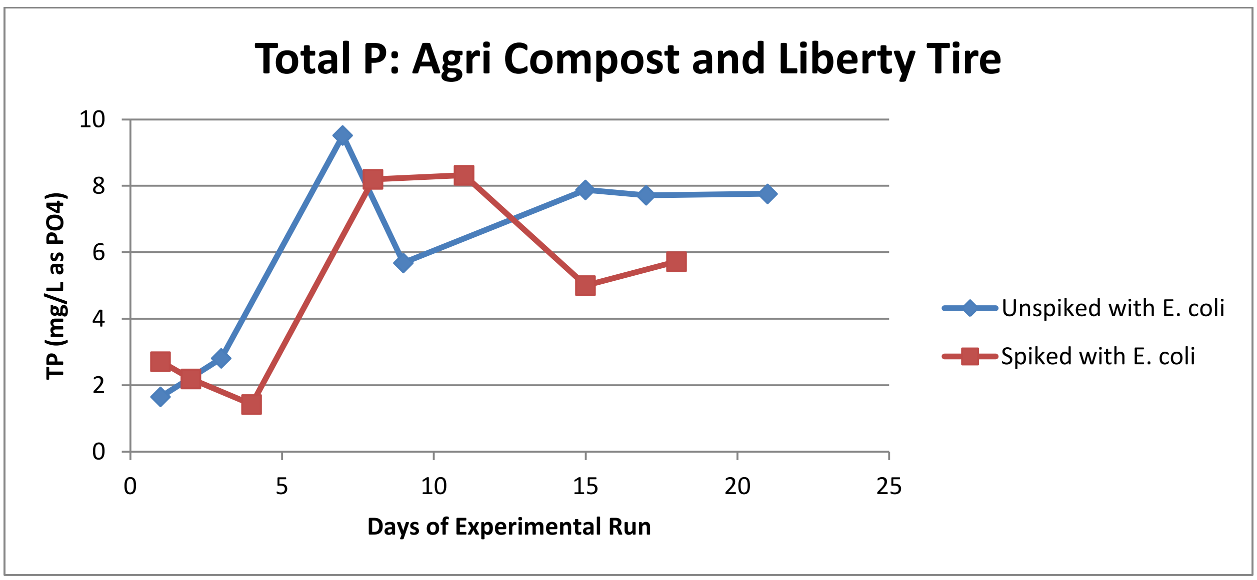

Figure 11 Comparison of spiked/non-spiked columns for Total Phosphorus in AgriCompost and Liberty Tire

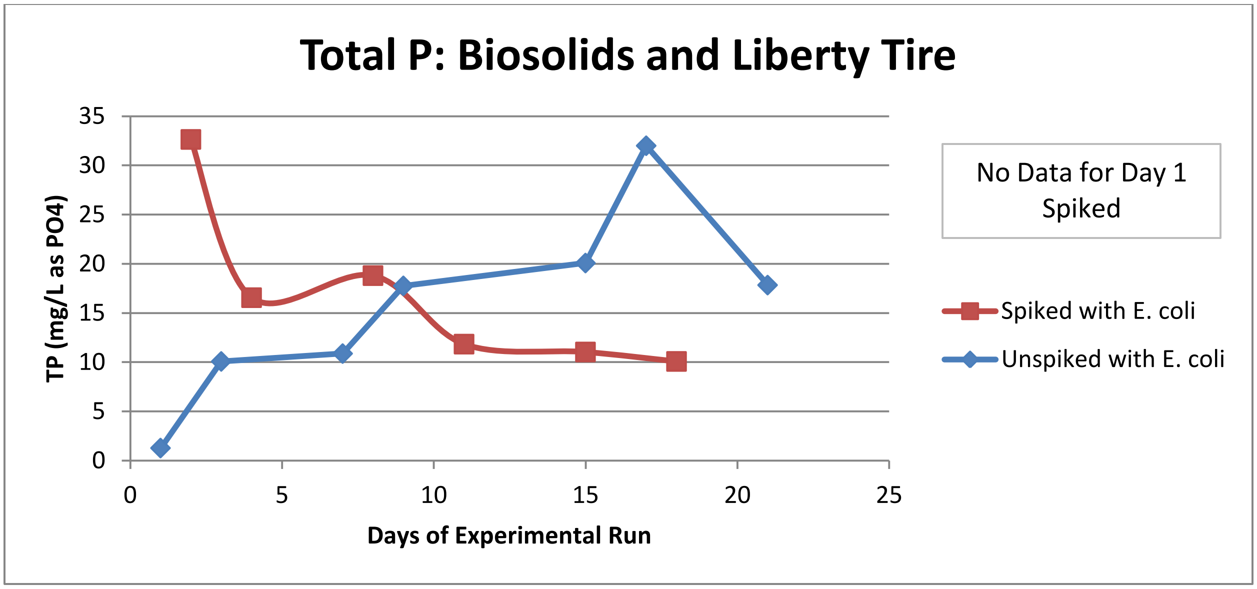

Figure 12 Comparison of spiked/non-spiked columns for Total Phosphorus in Biosolids and Liberty Tire

Chemical Oxygen Demand (COD):

The three figures show the COD results for the three media comparing columns with and without a spike of *E. coli* on day 2 (Figure 13, commercial green roof media; Figure 14, AgriCompost and crumb rubber, and Figure 15, biosolids and crumb rubber). The initial concentrations in the leachate are substantially different for each of the three media mixes (the largest being crumb rubber-biosolids, followed by the compost mix, and then the commercial media). Similarly, when comparing the initial concentrations between the spiked and unspiked runs, the leachates from the three media mixes were vastly different. For example, the crumb rubber-biosolids column had an initial difference of about 3,000 mg/L COD between the spiked and unspiked columns.

For the commercial green roof media (Figure 13), the effluents from both the spiked and un-spiked columns followed similar trends, assuming that the unspiked result on the second sampling day is an anomaly. For the AgriCompost and Liberty Tire (Figure 14), the un-spiked column effluent steadily increased over time while the spiked column effluent was steady for the first two weeks of the experiment and then decreased and steadied out for the remainder of the experiment. For the biosolids and Liberty Tire mixture (Figure 15), the un-spiked column steadily increased over time, while the spiked column decreased after *E. coli* was introduced into the media, again indicating the effect of an active microbial population on nutrient retention and preventing nutrient release.

When comparing the COD leachate concentration results with the respective values listed in Table 1, all three media (commercial, compost, and biosolids mixes) are significantly higher than the listed literature.

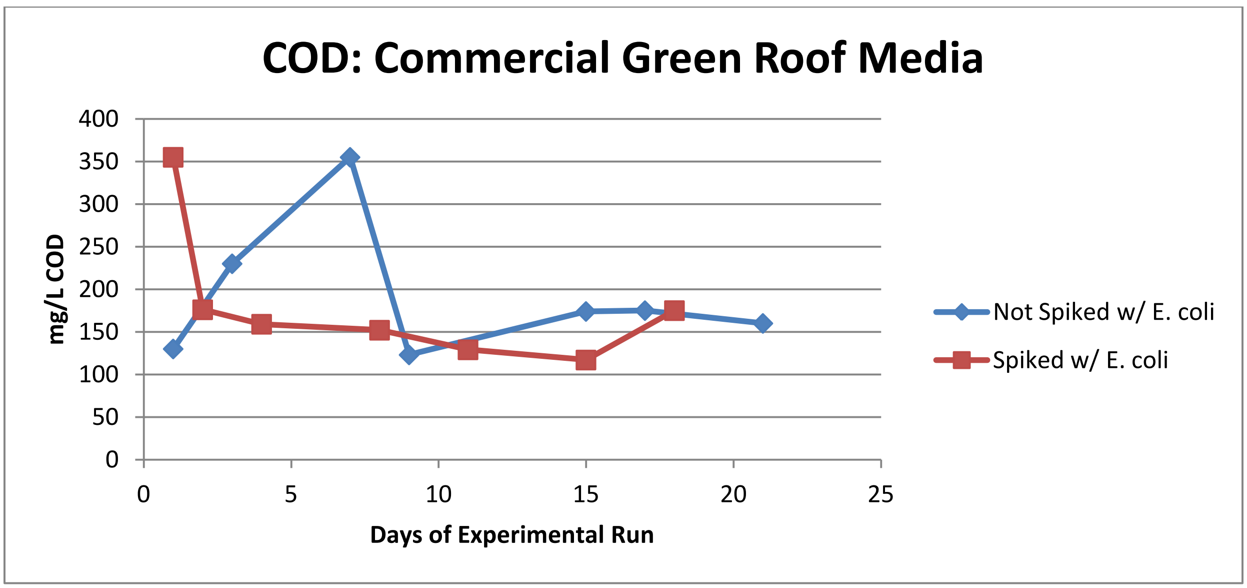

Figure 13 Comparison of spiked/non-spiked columns for COD in Commercial Green Roof Media

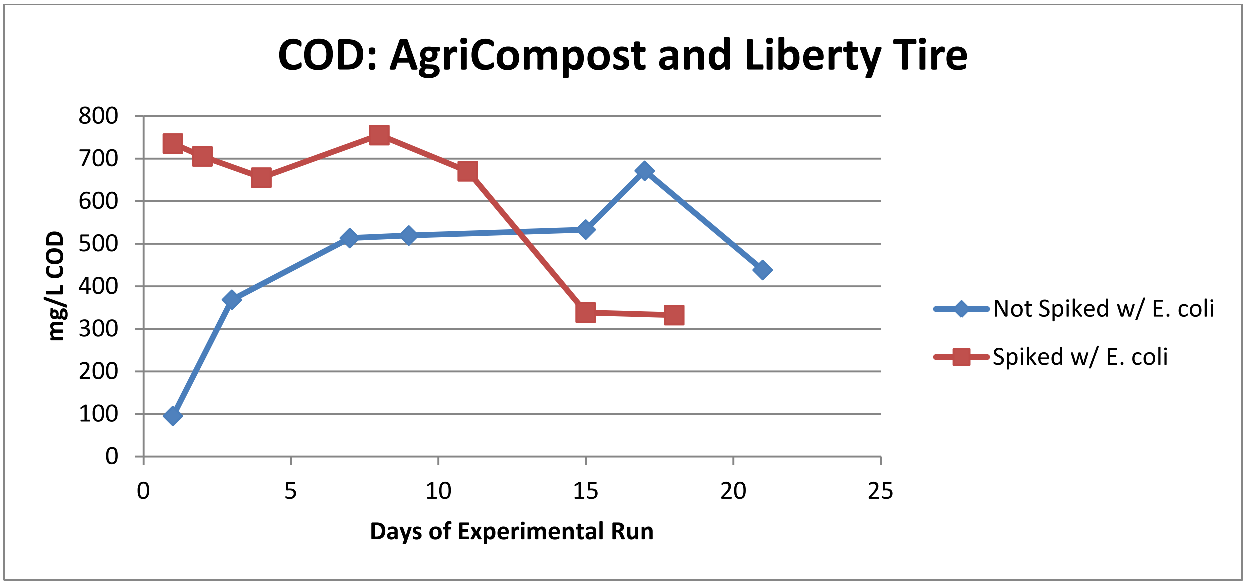

Figure 14 Comparison of spiked/non-spiked columns for COD in AgriCompost and Liberty Tire

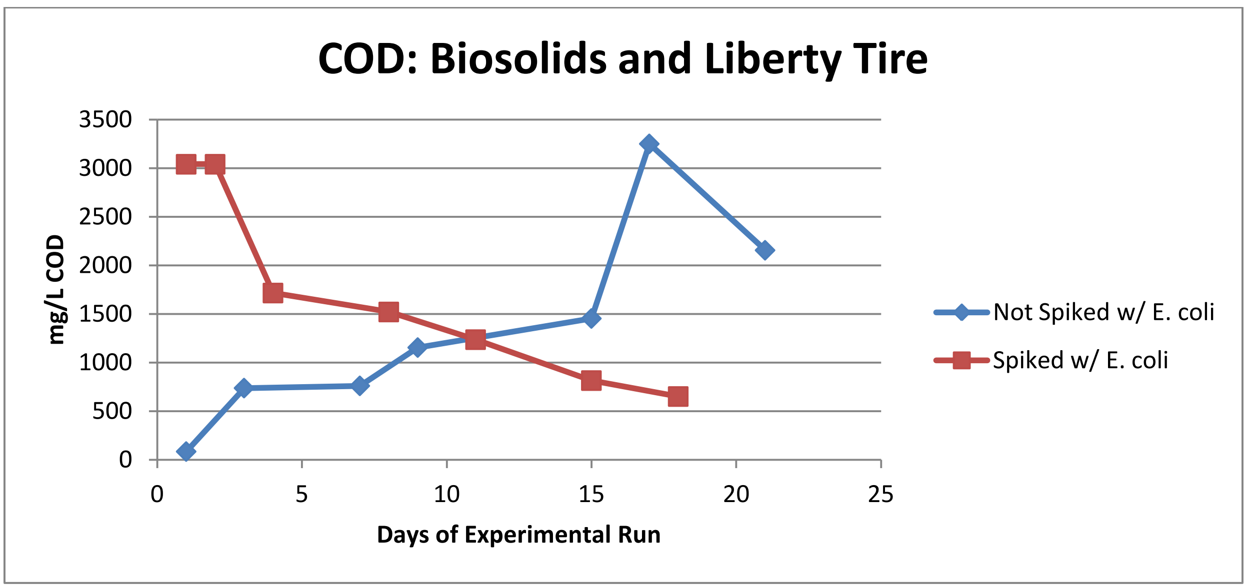

Figure 15 Comparison of spiked/non-spiked columns for COD in Biosolids and Liberty Tire

Copper:

The three figures below show the copper results for the three media comparing columns with and without a spike of *E. coli* on day 2 (Figure 16, commercial green roof media; Figure 17, AgriCompost and crumb rubber, and Figure 18, biosolids and crumb rubber). The initial copper concentrations in the leachate are very small in all three of the media mixes. They also are comparable between the spiked and unspiked runs.

For the commercial green roof media (Figure 16), the un-spiked column was steady throughout the experimental run, while the spiked column had a spike in the early days of the experiment. For the AgriCompost and Liberty Tire (Figure 17), the un-spiked column decreased over time, while the spiked column decreased but then increased after day 2 and held steady for the remainder of the experimental run. Based on the results for the entire run, it is possible that the initial decrease and increase are a result of variability and analytical challenges of colorimetric tests for copper. For the biosolids and Liberty Tire (Figure 18), both the spiked and un-spiked columns have similar trends and show no substantial difference between them.

As mentioned above, these results were analyzed using colorimetric techniques (Bicinchoninate Method). This method is sensitive to color interferences and several samples were moderately to strongly tea colored. To address this issue, many samples were diluted not because of concentration concerns but to address the color interference. This needs to dilute to address color interferences likely resulted in substantial variability in the results.

When comparing the copper leachate concentration results with the respective values listed in Table 1, the commercial media is similar to the water quality standards (the Maximum Contaminant Level Goal is 1.3 mg/L). However, in the recycled media, the copper leachate concentrations are substantially lower, indicating that copper release from crumb rubber is not substantial, which was an initial concern in the beginning of the project.

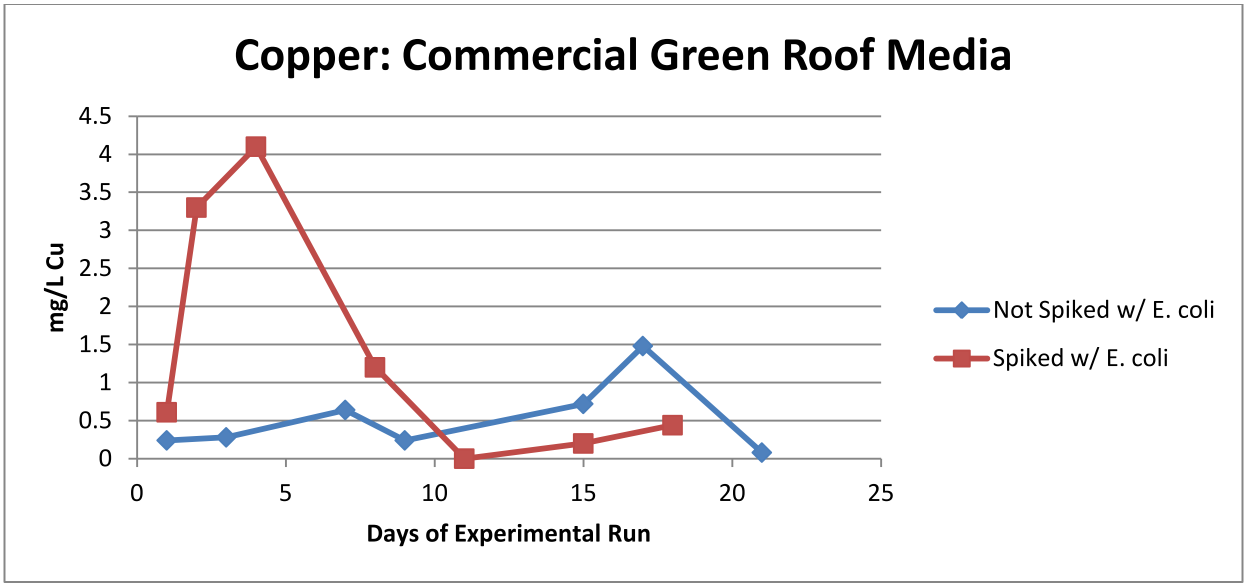

Figure 16 Comparison of spiked/non-spiked columns for Copper in Commercial Green Roof Media

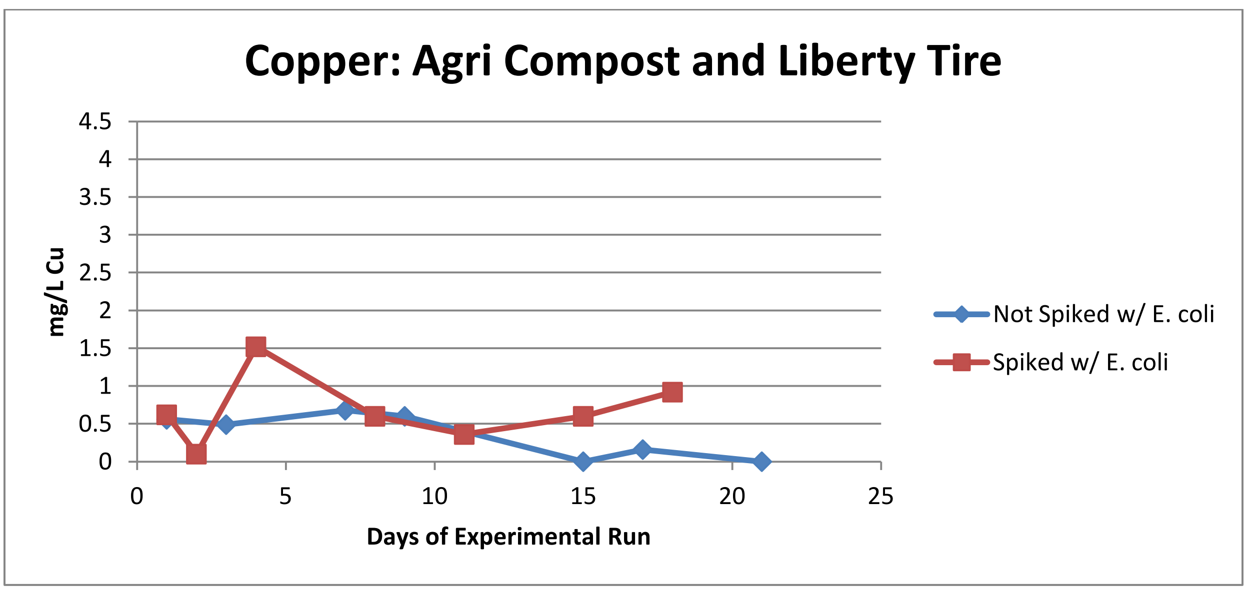

Figure 17 Comparison of spiked/non-spiked columns for Copper in AgriCompost and Liberty Tire

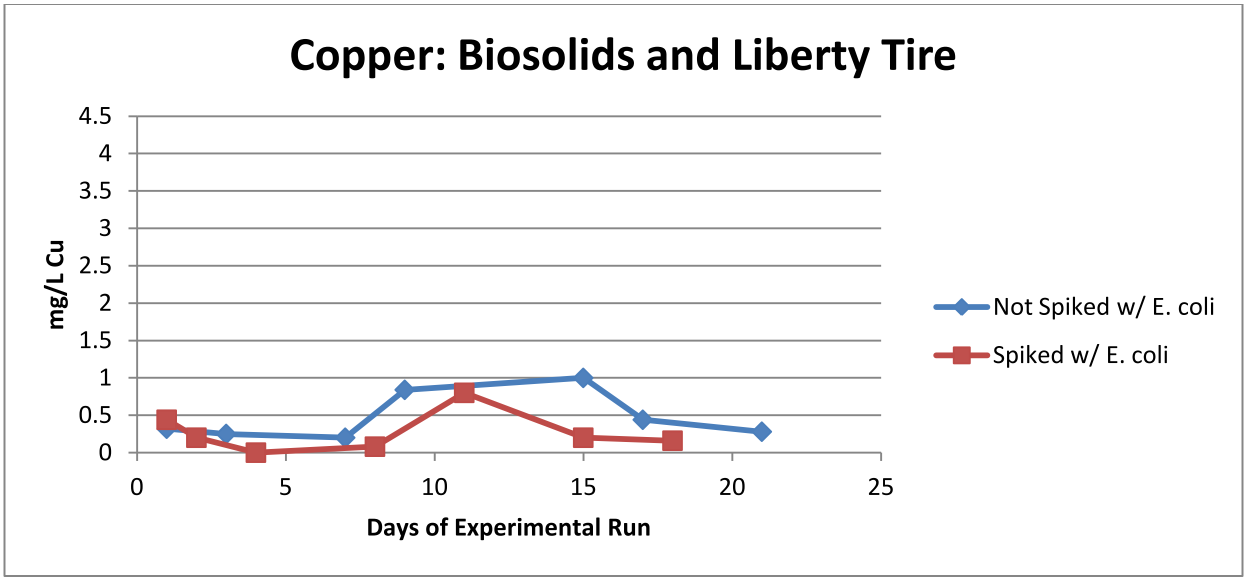

Figure 18 Comparison of spiked/non-spiked columns for Copper in Biosolids and Liberty Tire

CONCLUSION

Table 5 summarizes the results based on the impact of establishing an active microbial population. The microbial population was used to rapidly stimulate the impact of planting the roofs and allowing the microbial population to develop naturally. From the results, *E. coli* appeared to decrease or prevent an increase in concentration the following parameters: Nitrate, Total Nitrogen, and COD. The bacteria *E. coli* did not affect the effluent concentration for the following parameters: Ammonia, Total Phosphorus and Dissolved Copper. There were not enough results to do a statistical analysis.

Table 5. Summary of the Bacteria Impact on Effluent Leachate Concentrations.

The bacteria appeared to decrease or prevent an increase in concentration:	The bacteria did not affect the effluent concentration:
• **Ammonia** ○ Biosolids • **Nitrate** ○ Compost ○ Biosolids • **Total Nitrogen** ○ Compost ○ Biosolids • **Total Phosphorus** ○ Biosolids • **COD** ○ Compost ○ Biosolids	• **Ammonia** ○ Commercial ○ Compost • **Nitrate** ○ Commercial • **Total Nitrogen** ○ Commercial • **Total Phosphorus** ○ Commercial ○ Compost • **COD** ○ Commercial • **Copper** ○ Commercial ○ Compost ○ Biosolids

The testing showed that the initial leachate concentrations of one or more media are substantially different between each other. Because of this difference in initial concentrations in some of the media, it must be noted that the results may not be directly related to the spiking of *E. coli* and instead may be due to two reasons: (1) aging of either compost or biosolids media, or (2) ecological vacuum effect in the biosolids, and resultant change in nutrient availability due to the media being heat-dried.

Overall, the Class A biosolids used in this experiment are not as stable as the other two media (commercial and compost media); therefore their nutrient release (especially ammonia) is higher and increases without a well-established microbial population. However, if an alternative Class A biosolids with a stable microbial population was used, the results might be different. Compost is a slightly better choice in recyclable media, being more chemically stable than biosolids. The Suntech (commercial) media seems to be the most stable. A likely reason why the nutrient leachate concentrations were consistently not affected when *E. coli* was introduced into the columns in the commercial media was because the media might contain peat, a non-readilybiodegradable product. It must be noted that the columns used did not have any vegetation, therefore, the levels that are shown in the results section likely will be reduced by plant uptake once plants are introduced.

The recommendations for media component selection and installation

These results may be applied to the construction of green roofs. The recommendations are as follows:

- Minimize organic component to that needed for plant growth (measured as assimilable carbon).
- Install media as close to planting as possible so that plants can assist in establishing a healthy microbial population, since delays in plant installation allow for release of nutrients to harvesting system or to receiving water.
- Organic components should be aged and stable with respect to nutrient discharge.
- For copper, crumb rubber is not a concern, zinc still needs to be investigated.

Potential Future Research

Future research should focus on optimal green roof media mixes (for both plant growth and nutrient leachate reduction), a field-study using a real roof instead of a column, a repeat of this test but with improved methods (*i.e.* replicate columns), and a batch desorption/sorption test that would provide information on the mobility of nutrients and metals and their distribution in the green roof media.

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