Effects of Combining Controlled Release Fertilizer and Organic Matter to Nutrient Retention in Green Roof Media

by
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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 4, 2024

Keywords: green roof, rooftop garden, green roof media, controlled release fertilizer, organic matter

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Abstract

Rooftop gardening, a burgeoning sector within agriculture, repurposes existing urban spaces to cultivate plants for consumption, production, and environmental enhancement. This practice offers a sustainable solution for introducing agricultural opportunities to urban communities. As rooftop gardens become increasingly prevalent, research becomes essential to establish best practices for this emerging form of gardening. Currently, rooftop vegetable production faces various challenges, necessitating research into optimal watering regimens, fertility management, disease control, and more. Traditional green roof media (GRM) often suffer from poor water retention and high nutrient losses. Incorporating organic matter (OM) into GRM, alongside controlled-release fertilizer, shows promise in mitigating these challenges and ensuring consistent nutrient supply. To investigate the impact of organic matter on nutrient retention in GRM, we conducted a greenhouse container study. Green roof media, with varying levels of spent mushroom compost (SMC) amendment (2, 4, and 6 cm), were evaluated over two growing cycles (28 days). We measured crop biomass and Zinnia elegans (Zinnia) yield, as well as essential nutrient leachate concentrations, leaching fractions of applied water, and nutrient uptake. Our findings revealed that SMC amendment had no significant effect on crop growth and yield. However, it did lead to reduced leaching of essential nutrients such as phosphorus (P), iron (Fe), and manganese (Mn). Additionally, we observed a notable decrease in water loss through the GRM on average of 12% in 28 days. These results suggest that SMC holds promise as an effective OM source for GRM, offering potential benefits in water and nutrient retention.

Acknowledgements

I would like to first off thank my thesis advisor Dr. Daniel Wells for putting his faith in me for this entire project and thesis. It was a learning curve for me in many aspects, but he continued to believe in me through my failures. The project planning was not easy, but it was cultivated along the way. I am honored to have served such a wonderful program and learn so many skills to help me succeed in the future. I would also like to thank my committee members, Dr. Jeremy Pickens, Dr. Audrey Gamble, and Dr. Glenn Fain for helping shape this project to be successful. The ability to complete my research would not have been possible without Caroline Blanchard, Dorcus Lukwesa, Arnold Katende, Max Porter, Austin Bently, Evan Dulany, Jessica Parhos and many other graduate and undergraduate students. There were many long days but without their help it wouldn’t have been possible. I am thankful to Dr. Foshee, for the encouragement, good advice, and for cheering me on along the whole way. The friendships and memories I made with fellow graduate students here in the department are irreplaceable. I was honored to serve as the second president of the Horticulture Graduate Student Association. I want to thank my parents for all the encouragement and for raising me into the person I am that helped me succeed in this degree. My support system back home is a blessing. I give all the glory to God without his guidance and graces I would be nothing.

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Chapter I

Literature review

Benefits of Rooftop Gardens

Rooftop gardening has emerged as a sustainable solution for vegetable cultivation, offering numerous benefits to the urban environments in the 21st century. With a decline in farmers and farmable land and the continuous destruction of natural habitats for urban development, finding a sustain able alternatives for food production becomes increasingly crucial (USDA 2023). Green roofs (GR’s) also known as living roofs, eco roofs, or vegetated roofs (Abass *et al.* 2020), utilize existing urban space for secondary purposes. They provide various advantages including urban heat island effect mitigation, energy conservation, volume and quality of stormwater runoff, aesthetic values, economic impact, and improvement of mental health (Shafique et al. 2018, Jamei et al. 2021, Ávila-Hernández et al. 2020), Peck et al. 1999, Bratman et al. 2015). Initiatives by organizations like Green Roofs for Healthy Cities since 1999 underscore the importance of increasing green infrastructure (Peck Steven 1999). While researchers may define GF’s differently, they generally refer to building roofs covered with vegetation and growth medium. GF’s can be flat or sloped and function both as a roof and a habitat for vegetation (Yu et al. 2017). Additionally, rooftop gardens, also known as Zfarming or Zero acreage farming, are gaining attention (Specht *et al.* 2014). However, existing literature primarily focuses on the environmental impact of GF’s and lacks research on vegetable quality, growth, and production. Historically, rooftop gardens have roots dating back to ancient civilizations, such as the Hanging Gardens of Babylon and rooftop gardens in ancient Rome, where they were used for royal events. Even Vikings utilized rooftop gardens to protect their homes and buildings from the elements (Peck *et al.* 1999). Today, these historical concepts are being reimagined with modern technologies to address contemporary challenges.

Intensive vs. Extensive

There are two main engineering categories outlined for GR's: intensive and extensive. Intensive designs contain deeper soil that can accommodate larger plants with deeper root systems. This type of GR requires more intensive care and a higher nutrient demand than an extensive GR. extensive GR design incorporates shallow substrate and low-maintenance vegetative species like grasses, sedums, and native grasses that do not require irrigation (Berndtsson 2010, FLL 2018) A debate on how to classify the differences between the two types of GR's still exist.

Researchers argue that depth classifies a structure as intensive or extensive, but a conclusion on the appropriate depth was never determined. American Hydrotech, a rooftop design company, classifies intensive as soil depths from 150 mm to 900 mm and extensive <150 mm (American Hydrotech 1977) However Berndttson (2010) classifies intensive as >300mm and extensive as < 300 mm (Berndtsson 2010). In addition to intensive and extensive GR's, the German Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V (FLL) Identifies a third type: simple intensive GR. which is lower maintenance and is described as usually containing ground cover plants, grasses, perennials, and shrubs. (FLL 2018). Design considerations are important in material selection of GR's, as it can affect structural integrity. FLL defines maximum water capacity for construction of a GF by the amount of water held after it has been saturated and dripping for two hours (FLL 2018). The weight of this water must be considered in the design load of the GR. Older buildings are often not designed and engineered for the heavy weight load added by the substrate and water holding capacity of the GR; therefore, many buildings have added a shallow extensive GR instead of a deeper intensive GR (Getter and Rowe 2006). This requires less construction and modifications to a building and has a positive effect on the overall environment. Generally, construction layers for both intensive and extensive are similar containing vegetation, media layer, a fine netting, and drainage system leading to the storm water drains (Berndtsson 2010).

GR design and construction standards are still not fully implemented in the United States due to lack of research and understanding of GR's. The American Society for Testing Materials (ATSM) has been establishing English guidelines over several years, but it is unknown how binding these guidelines are in the United States (Blackhurst et al. 2010). Guidelines developed by the FLL were the first guidelines to be used for GR construction in the world, and they were not published in English until the 1990's (FLL 2018).

Energy Conservation and Urban Heat Island Effect

The urban heat island effect (UHI) is a phenomenon that occurs when natural landscapes are replaced with surfaces such as pavement, asphalt, and buildings that absorb and retain heat. The excess heat within urban areas causes a series of ecological and environmental effects on urban climates, soil properties, material cycles and energy flow (Yang *et al.* 2016). It has negative effects on the health and wellbeing of people and on the overall environment (Kotzen 2018). The UHI effect is increased by a higher density of buildings with low albedo meaning these buildings do not reflect solar energy at high rates and hold more solar radiation (Di Giuseppe and D'Orazio 2015). GR's provide positive cooling effects in urban areas, increased energy savings (Di Giuseppe and D'Orazio 2015, Susca et al. 2011) and reduce temperatures compared to conventional roofs (Di Giuseppe and D'Orazio 2015).

Implementation of GR's showed positive impacts on UHI effect in hot-humid, temperate, and dry climates (Jamei *et al.* 2021). In temperate climates GR's reduced demand for cooling energy by up to 99% and, at the same time, increased demand for heating energy by 25%. In places with hot weather, the GR reduced the building's internal temperature by up to 4.7 ℃ (Ávila-Hernández *et al.* 2020). A 2℃ difference was measured in New York City's most and least vegetated areas. If GR's were used more frequently in densely urbanized areas, energy cost could be reduced by up to 30-100% (Susca *et al.* 2011). Bass et al., predicted that a GR could have a 1% reduction in temperature for 50% roof coverage (Bass *et al.* 2003). In addition, plant species can influence cooling effects. Most of the cooling effect produced by C3 and C4 plants is produced by respiration. While CAM (Crassulacean Acid Metabolism) plants create a cooling effect through their canopy, solar energy absorption, and insulation (Cao *et al.* 2019). The addition of OM (Organic Matter) to GR media (GRM) also advances the cooling capacity of GRM because of the increased moisture retention allowing for greater evaporative cooling (Eksi *et al.* 2015).

Urbanization has effects on the natural water cycle and shifts rainfall patterns globally. (Thielen et al. 2000, Hao 2010). Studies have shown increases in rainfall in rural areas downwind of dense cities (Ackerman et al. 1978,Thielen et al. 2000). From 1971 to 1975, 15 to 45 km downwind of St. Louis, cloudiness increased, rainfall increased, and severe weather increased (Ackerman *et al.* 1978). Increases in heavy industry 30 miles west resulted in increased rainfall, thunderstorms, and hail in La Porte, Illinois (Changnon 1968) Rural surfaces receive more rainfall than urban surfaces (Thielen *et al.* 2000). Parklands and greenspaces in major cities are responsible for a higher occurrence and higher volume of rainfall according to climatic data (Makhelouf A 2009, Patel et al. 2021). Increased rainfall helps cool cities, but it has also shown positive effects on air quality in cities (Makhelouf A 2009).

Intensive GR's are comparable to urban forests as a strategy to remove air pollutants (Nowak *et al.* 2006). Rowe (2011), demonstrated through modeling the potential GR's have at decreasing atmospheric CO^2 on the campus of Michigan State University. Using this model MSU could avoid 3,640,263 kg CO^2 emitted per year in electricity and natural gas consumption combined for every 1.1 km^2 of flat roof surface converted to a GR system.Rowe compared this to the equivalent of taking 661 vehicles off the road each year (Rowe 2011). Models can be used to predict the benefits GR's have on air quality, however case studies that focus on air quality are limited.

Volume and Quality of Stormwater Runoff

In addition to mitigating the UHI effect, GR's are also being studied as a stormwater management tool. Urban areas generate more runoff than rural areas due to higher percentages of imperviable surfaces. Rainfall retention on vegetated roofs averaged 82.2% versus gravel at 47.7% retention (Vanwoert *et al.* 2005). An extensive GR has retention ranging from 10% to 60% (Shafique *et al.* 2018). Vegetation contributes to a higher water retention rate on GR's (Beecham and Razzaghmanesh 2015). In Table 1. Cater and Rasmussen (2006) investigate an inverse relationship that occurs between rain and the retention of a GR(Carter and Rasmussen 2006).

Storm class	Rainfall (mm)	Retention
Small storm	<25.4	88%
Medium storm	25.4-76.2	54%
Large storm	>76.2	48%
Carter and Rasmussen 2006		

Table 1. Relationship between rain fall and retention on green roofs.

Studies quantifying storm water runoff on GR's generally indicate a reduction in runoff compared to conventional roofs. Substrate depth has been shown to be a major factor in the effectiveness of runoff in GR systems (Berndtsson 2010).

Runoff quality from GR's has also been shown change. A certain amount of water is intended to be held in the substrate and used for plant uptake and evaporation. Water quality improves with time as the substrate and vegetation stabilize. The poorest nutrient runoff quality occurs in the early stages of the GR's lifespan (Lim 2023). Often GR's with vegetation that require added fertilizer will cause leaching of NPK into the storm water system. Overall, this influx of nutrient decreases water quality (Teemusk and Mander 2011).

Human Health Benefits of Urban Farming

Urbanization has considerable positive attributes, but mental health is not one of them (Kotzen 2018). Increases in urbanization make rooftop gardens more popular and have been associated with positive mental health impacts (Mas et al. 2020). People who spend more time in nature tend to have a better outlook on life than those that do not (Bratman et al. 2015). Rooftop gardening is a way to bring nature into urban areas to increase overall mental health. Rooftop gardens provide fresh air, sun, and exercise while also providing education about healthy eating habits (Mandel Lauren 2013). Over 250,000 adults and children reported better general health with an increased amount of green space in their immediate environment (Mandel Lauren 2013). Rooftop gardens use fewer chemicals because of reduced weed, disease, and insect pressures. adding to the positive effects of GR's on environmental and human health (Walters and Midden 2018).

During the Covid 19 pandemic, interest in rooftop gardening began to grow in urban planning. In 2020, interest in farming increased as many countries experienced empty grocery stores. Those in cities with no garden space were left at a disadvantage. An increase in publications about urban gardening and simple ways of food production began to appear online. Publications focused on giving people hope that gardening could still be done in urban settings (Sofo and Sofo 2020).

Nutrient use or Application Efficiency

Rooftop gardens use soilless substrates that are porous, lightweight, and intended to drain water quickly (Kong *et al.* 2015). Rooflite ® intensive ag (Skyland USA LLC, Avondale, PA) a soilless substrate designed for rooftop farms, has developed a blend for extensive GR's that contains 12 light weight mineral aggregates like HydRocks® (calcining clay), pumice, or shale that are all natural, non-degradable soil enhancers with additional organic components included for increased cation exchange and moisture holding capacities (VanWoert et al., 2005). Organic and mineral additives for both intensive and extensive GR substrates are the same (e.g., peat, humus, wood chips, sand, lava, or expanded clay). These materials have been studied and proven to have ideal permeability and optimum water retention (Green Roofs | GSA 2023). FLL recommends using 4–8% organic matter by volume for extensive GR's (FLL 2018). However, the high porosity limits the water availability for plants which also limits the nutrient retention making it difficult to grow high water and nutrient demanding plants.

Nutrient management and moisture content are two major components for intensive rooftop systems. A strategy to increase water holding capacity and nutrient retention is to add a source of OM. The addition of OM, usually through compost addition, has multiple benefits to soil health, including improved water retention capacity, increased microbial activity, improved soil texture, reduced temperature extremes, and releases nutrients more constantly and slower (Yang et al. 2021,Getter and Rowe 2006). According to Bates et al., higher OM in GRM resulted in increased plant coverage; however, during drought conditions treatments with higher OM levels were negatively impacted. Rooftop substrates maintain low OM levels to prevent rapid decline of healthy plants under drought stress, highlighting the importance of irrigation (Bates et al. 2015). OM at 10% is optimal for growth without irrigation but 50% with applied irrigation is optimal (Nagase and Dunnett 2011). OM was shown to improve the physical properties of GRM by reducing the dry bulk density and increasing water holding capacity. A compost as an OM source has the potential to decrease air space in the media; and was shown to maintain adequate aeration for plant growth (Graceson *et al.* 2014). A concern with adding compost as an OM source to GRM is the additional weight load added by the increased water holding capacity. Coarse composted green waste is reported to be less effective than fine composted green waste at enhancing water holding capacity (Durhman *et al.* 2006). However, even with a fine composted material studies have shown that GRM is below the maximum water holding capacity level of 65% v/v set by the German FLL (2008), and even treatments amended with fine green waste municipal compost substrates remained below the 20% v/v minimum the Germans recommend (Graceson et al. 2014). OM can also be used as a fertility plan. Increased growth and chlorophyll content in olive trees were observed when OM was amended in GRM (Kotsiris et al. 2013).

The fertilizer that is recommended by FLL is a coated slow-release fertilizer (FLL 2002). Using controlled release fertilizer reduces nutrient runoff versus conventional fertilizer (Anwar *et al.* 2007). When used on their own, inorganic fertilizer and OM have disadvantages, but together bring certain advantages to rooftop gardens. Integrated fertility management is necessary to take advantage of both total nutrients and available nutrients, which are increased when using inorganic fertilizer and OM together. This promotes biological activity and physiochemical characteristics within the medium (Yang et al. 2021). Results from a field study suggest that organic fertilizer in a composted material releases N slowly in the early stage and showed a significant residual effect, while controlled- release urea supplied N quickly in the first 2 months. This suggest that the use of organic fertilizer such as a composted material combined with controlled release fertilizer will have an immediate effect and last longer (Yang et al. 2021). The combination of manure and inorganic fertilizer increased crop productivity, crop quality, and maintained fertility in basil plants (Anwar et al. 2007). Yang et al., studied the movement of P with the use of integrated fertility management. The reduction of P by OM amendment was related to the stimulation of microbial activities, which incorporated water-soluble P from applied chemical fertilizer into organic fractions and retained more P in soil, which was made available to plants (Yang *et al.* 2008). Ideally if OM has this effect on soils, it could have a similar effect on GR growing media.

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Chapter II

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Abstract

Rooftop gardens are increasingly recognized as a valuable means of introducing green spaces to urban areas, with vegetable cultivation emerging as a popular application for these environments. However, the intensive nutrient requirements of vegetables necessitate careful management to prevent excess nutrients from entering stormwater systems. Given the limited understanding of nutrient retention enhancement in green roof media, this study seeks to assess the impact of spent mushroom compost (SMC) as an organic matter source on nutrient retention.

To investigate whether increased organic matter content in green roof media could mitigate nutrient loss and reduce water usage, we conducted a greenhouse container study. GRM and GRM with three amended compost treatments applied to the top of the containers, consisting of 2 cm, 4 cm, and 6 cm layers of SMC were analyzed. Polymer coated fertilizer (Harrell's 12N – 5.5P – 9.9K) served as an inorganic fertilizer source for the experiment. We monitored crop biomass and yields of Zinnia elegans (Zinnias) over two growing cycles spanning 28 days. Additionally, we measured essential nutrient leachate loss, leaching fractions of applied water, nutrient uptake, and nutrient availability in the media solution. The addition of SMC did not significantly impact the biomass or yields of Zinnias. However, notable changes were observed in the leaching dynamics of essential nutrients. Phosphorus, iron, and manganese exhibited reduced leaching when SMC was added. Phosphorus leaching was reduced 28% by 4 cm of SMC. Containers treated with SMC experienced a leaching faction of municipal water through the system decreased by approximately 13%, 12%, and 13% at 2, 4 and 6 cm by day 28. SMC has the potential to reduce the environmental impact of nutrient loss from GRM.

Introduction

Green roofs (GR's) are gaining popularity around the world. Countries such as Germany have introduced programs to promote GR technology for the improvement of environmental management (Teemusk and Mander 2011). Research indicates that GR's have many positive impacts such as reducing cooling demands of buildings, mitigating the urban heat island effect, reducing storm water runoff, sequestering carbon dioxide, improving aesthetics, creating wildlife habitats, and providing noise reduction (Blackhurst *et al.* 2010). Using GR's to grow vegetables has been researched in recent years because of its potential too to ensure a consistent food supply in urban areas (Shariful Islam 2004). Evaluation of vegetable production on rooftop gardens has shown to be successful but lack of knowledge of the media used and unknown fertility recommendations reduces interest in growing these high value crops (Whittinghill et al. 2013). Roof top gardens use inorganic media with a low dry bulk density to reduce the impact on the buildings load bearing capacity (Graceson et al. 2014). As construction of rooftop gardens continue to increase, proper research on the media used is important to aid in the best plant production.

Nutrient and water management are concerns in rooftop gardening because of the characteristics of the media used and the harsher environments in which plants are grown. For example, intensive exposure to sunlight, strong winds, and often shallow substrates can limit water and nutrient efficiency. These substrates are classified as green roof media (GRM) and are typically blends of peat, humus, wood chips, sand, lava, and expanded clays, with the largest proportions by volume and weight coming from expanded clays (Kong *et al.* 2015). GRMs need to be relatively lightweight they are often porous and drain readily. Commercial GRMs are available for intensive or extensive GR systems, which refers to the depth of the GRM. Extensive GR's have shallow substrates (<150 mm) while intensive GR's have deeper substrates (>150 mm) (FLL 2018). Because GRMs need to be relatively lightweight and drain quickly watering needs are often high, this is particularly important for intensive GR systems that often feature plants with high water demands compared to extensive GR counterparts which often contain drought-tolerant succulents (Durhman et al. 2006). Additionally, GRMs tend to have relatively low cation exchange capacities when compared to organic substates or mineral soils, increasing the need for supplemental nutrient addition. An additional challenge for the initial stages of intensive GR systems is the lack of microbial activity in GRM (Fulthorpe et al. 2018). These medias are derived mostly from dry mineral materials and are necessarily sterilized, negatively affecting the overall microbiome (Fulthorpe et al. 2018, John et al. 2014). This can be problematic for production of vegetables especially when establishing intensive systems.

A potential solution that could address water and nutrient retention in GRM and add beneficial microorganisms is the addition of organic matter (OM). In agricultural soils, supplementing OM improves soil structure, nutrient and water retention, increases biodiversity, and decreases risks of soil erosion (Lal 2009). A common, commercially-available OM product is spent mushroom compost (SMC), which is the composted leftover substrate used in mushroom production. Mushroom production substrate materials vary but are typically chopped straw, poultry manure, and gypsum (Uzun 2004). Like other composted OM products, SMC promotes soil microbial activity, and has been shown to improve plant yields (Uzun 2004, Appleby-Jones 2014, Lohr et al. 2022).

In some plant production systems, OM can be added in high enough quantities that it is used as a source of nutrients. When SMC is used as a fertilizer, nutrients are released over time via mineralization, the rate of which is dependent on moisture level and temperature (Uzun 2004). In the establishment phase of a garden, it is advantageous to provide supplemental fertilization for young plants. On rooftop gardens, supplemental fertilization can be applied via synthetic fertilizers in the form of agricultural grade granular fertilizers, controlled release fertilizers (CRF) (Emilsson et al. 2007, Pavlou et al. 2007), or water-soluble fertilizers (Walters and Midden 2018), Organic fertilizers, may also be used and derived from form of manure or animal byproduct, or a combination thereof (Uzun 2004). While OM is not normally used as a sole nutrient source for rooftop gardens it can supplement plant nutrition. For example, N from SMC was reportedly mineralized at an average annual rate of 15% in a sandy loam soil (Uzun 2004), which reduces N leaching potential, but may not be suitable to support plant growth, especially as a sole nutrient source. Therefore, we conducted an experiment to determine the effects of SMC addition to GRM, in combination with a CRF, during the establishment phase of a rooftop garden on water retention and nutrient leaching potential.

Materials & Methods

Treatment Application and Experimental Setup

On 4 June and 13 July 2023, 105 ‘Benary’s Giant Salmon Rose’ seeds (*Zinnia elegans J.*) were sown in a seedling tray and germinated under greenhouse conditions. Seven days after seeding, on 11 June and 20 July 2023 seedlings were transplanted into 18-cell flats and grown for two additional weeks until transplanting into experimental containers. Developing seedlings were irrigated with a nutrient solution containing 200 mg L^1 N from Harrell's Prosolubles fertilizer 20N-4.6P-16.6K (Harrell’s LLC., Lakeland, FL).

On 3 July and 10 August 2023, 40 uniform zinnias were transplanted, one per container, into 40 separate experimental 3.7-L elite nursery containers (The HC Companies®., Twinsburg, OH). Each of the 40 containers had been previously filled with 454 g (dry mass) of Hydrotech’s LiteTop ® Intensive growing media (Hydrotech Membrane Corp., Canada, Montreal) and topdressed with either 0, 2, 4, or 6 cm of Black Velvet® SMC (Black Gold Compost Co. Oxford, Fl), which weighed 0, 111, 222, and 333 g, respectively (dry mass). After transplanting, a controlled release fertilizer (CRF) (Polyon 12N-5.5P-9.9K; Harrell’s LLC., Lakeland, FL) was topdressed at a rate of 2010 kg ha^{-1} of N (38.8 g/pot). For each treatment (0, 2, 4, or 6 cm SMC) there were 10 replicate experimental units, seven of which were randomly spaced across a greenhouse bench and three of which were used for leachate analysis., a One bamboo stake was placed in each experimental pot and used to trellis plants as they grew.

Leachate collection

Three experimental containers (3.7-L containers containing one zinnia plant each) from each treatment were fitted into an 18.9-L bucket with a lid in such a way that leachate from the experimental unit was collected in the bucket. To accomplish this, a circular hole, slightly larger than the bottom and slightly smaller than the top of the 3.7-L experimental container, was cut into each bucket lid. One experimental container was set into the hole in each bucket lid and the resulting seam was sealed with silicone. The bucket lid was then affixed to the bucket to exclude water that did not pass through the experimental container (Figure 1).

Watering Regimen

On the day of transplanting into experimental containers (0 DAT) zinnias were watered thoroughly using 1 L of municipal water. From 1 DAT to 28 DAT, each experimental pot was hand-watered with 500 ml of municipal water two times per day (7:30 am and 4:00 pm). Irrigation rate is based on an irrigation schedule and volume being used at the time in the Rane Culinary Science Center Rooftop Garden at Auburn University located in Auburn, Alabama USA (Auburn, AL, USA).

Growth Measurements

On 3, 10, 17, 24 and 28 DAT, on each experimental unit, plant height (cm) was measured with a meter stick from the substrate surface to the top of the plant, lateral shoots, borne from the main stem, were counted and summed to determine lateral shoot count, flowers showing color were counted and summed to determine flower count, open flowers were measured across their widest width to determine flower size, and leaf greenness was estimated as SPAD index (SPAD-502; Konica Minolta, Inc. Osaka, Japan). At 28 DAT, all flower buds, whether showing color or not, were counted and summed to determine final bud count, open flowers were weighed to determine flower weight, and shoot fresh weight (SFW) was determined by severing plants at the substrate surface and weighing the entire shoot portion. Plant shoots were then dried in a forced-air drier, weighed to determine shoot dry weight (SDW), and samples from the total shoot mass were analyzed for total nutrient content (Waters Agricultural Laboratory, Camilla, GA).

Water and Nutrient Measurements

Water leached through experimental units was collected, as previously described, and weighed weekly to determine leachate volume, and leaching fraction.

Leachate volume

Volume (L) = $\frac{(weight\ of\ bubket\ lb\ )}{2.204\ ^{lbs}/_{1L}}$ = Volume (L) of leachate

Leaching fraction

LF = Cumulative volume of water applied / Cumulative volume of water collected * 100

Aliquots (500 ml) from collection buckets were collected three times throughout the experiment (DAT 7, 17, 28) and analyzed for Nitrate-Nitrogen, Ammonia-Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, Sulfate, Boron, Zinc, Manganese, Iron, Copper, and pH (Waters Agricultural Laboratory, Camilla, GA).

Statistical Analysis

Data were analyzed using an analysis of variance (ANOVA) via PROC GLIMMIX and means were separated using Tukey's HSD test in SAS 9.4 software (SAS Institute, Cary, NC). Trial date was not a significant main or simple effect and was thusly placed into a RANDOM statement to account for natural variance not related to experimental treatments. As a result, only treatment (0, 2, 4, or 6 cm SMC) was analyzed for effects on response variables.

Results

Plant Growth and Biomass

There were no differences in plant height, flower size, flower weight, SPAD index, lateral shoot count, bud count, or flower count between treatments (Table 2.1). Foliar potassium

(K) concentrations increased with increasing addition of SMC (Table 2.2). Foliar boron (B) increased as SMC increased while foliar Zn, Mn, Fe, and Cu decreased as SMC increased (Table 2.3).

Leachate Analysis

Addition of SMC, regardless of amount, decreased the amount of ammonium N (mg) leached during the experimental period by averages at 2 cm of approximately 47%, 95%, and 97% at 7, 17, and 28 DAT. At 4 cm 60%, 96%, and 65% at 7, 17, and 28 DAT, and at 6 cm 56%, 93%, and 93% respectively (Figure 2) but did not affect total N or nitrate-N (Table 2.2). Similarly, the addition of SMC decreased the amount of P leached during the experimental period at 2 cm by averages of 39%, 35%, and 35% at 7, 17, and 28 DAT. At 4 cm 35%, 60%, and 58% at 7, 17, and 28 and at 6 cm 29%, 50%, and 21% at 7, 17, and 28 DAT (Figure 3). Cumulatively SMC led to a reduction of leached P by approximately 24%, 28%, and 20% at 2, 4, and 6 cm (Table 2.4). The most effective treatment in reducing leached P throughout the experiment was the 4 cm treatment. 10Despite a decrease in leached P and ammonium N over the experimental period, a positive linear trend was observed of leached K at 2 cm by approximately 37%, 43%, and 36% at 7, 17, and 28 DAT. At 4 cm 51%, 52%, and 47% at 7, 17, and 28 DAT, and at 6 cm 47%, 64%, and 60% at 7, 17, and 28 DAT. Leached S increased over the experimental period (Table 2.5). Of applied micronutrients Fe and Mn (Figure 4 and 6) decreased leaching with the addition of SMC, while leached B increased over the experimental period (Table 2.6). The leaching faction of municipal water through the system decreased by approximately 13%, 12%, and 13% at 2, 4 and 6 cm by day 28. (Figure 6).

Discussion

Nutrient dynamics

Nitrogen

Nitrogen (N) is the highest demanding nutrient in plant production and is also a concerning pollutant. Of the two dominant plant-available forms N-forms, NH_4^+ leached significantly less in containers treated with SMC, which can be attributed to the linear increase in cation exchange capacity with increasing rates. However, the most dominant form of N plants uptake is NO_3^-, which was not influenced by SMC. Overall total N was unaffected by SMC. Clay soils are known to indirectly play a significant role in reducing NO_3^- leaching because of the increase in water holding capacity associated with clay soils (Kanthle et al. 2019). GRM and SMC in this study both consisted of (84.8% sand 12.8% clay and 2.72% silt.) and (85% sand 12.28% clay and 2.52% silt) both classified as a sandy loam. The addition of OM often increases the Carbon to Nitrogen C:N ratio, this was not observed with SMC. Carbon Soils with higher carbon concentrations may have minimally reduced leaching of N compared to those with lower carbon concentrations, as denitrifying bacteria that will utilize N in anaerobic conditions and subsequently reduce leaching (Kanthle *et al.* 2019). Targeting ammonia-N leaching specifically, it would be important to use a material containing higher silt and clay content (Gaines and Gaines 1994). However, this may not be an acceptable solution to add to GRM due to increased bulk density and water holding capacity that may exceed the design load of a structure. The Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V (FLL) limits the amount of silt and clay content to that is allowable for rooftop gardens (FLL 2018). A potential strategy to control NO_3^- leaching is to reduce water usage on rooftop gardens, which could be facilitated by SMC, as evidenced by the decrease in the leaching fraction.

Phosphorus

The primary cause of eutrophication is phosphorus (P). Stormwater systems accounted for 9.2% of total phosphorus load discharged to Baltic Sea in 2012 and with increasing prevalence of GR's there is potential for higher P discharge (Karczmarczyk *et al.* 2020). Studies have concluded that leached P can be reduced using SMC either though soil colloid adsorption to Fe/Mn oxides (pH<7) or precipitation to Ca under increased OM additions (Lou et al. 2015, Borggaard et al. 1990) Positive correlations were observed between leached P and Fe (r = 0.5267) and leached P and Mn (r = 0.6606), suggesting that interactions among these nutrients may contribute to decreased leaching of all three nutrients (Li *et al.* 2021). Sandy soils amended with organic matter using CRF have shown the best results in phosphorus utilization and efficiency, resulting in reduced leaching (Yang *et al.* 2008).

Potassium

Potassium (K) can be considered the second most important nutrient to N and is vital in osmoregulation, membrane potential regulation, cotransport of sugars, stress adaptation and growth (Johnson *et al.* 2022). In this experiment plants showed a positive linear trend in the uptake of K as SMC increased. Luxury consumption of K is the probable cause of the increase in uptake of nutrients due to increased K concentrations in added SMC (Bartholomew and Janssen 1929). Given the significant addition of available K by SMC, coupled with the typically lower retentive capacity for K in loamy sand soils (Potassium in the soil - Potash Development Association (PDA) 2019), it is plausible that the increased leaching of K can be attributed to the addition of SMC. K-leaching typically decreases in soils with a higher pH because K ion can replace Ca ions more easily. However, in this experiment the opposite trend was observed indicating that K was provided in excess obscuring any reduction effects by the increased pH.

(Yakovleva *et al.* 2020). K is soluble in nature but does not pose any specific environmental issues (Goulding *et al.* 2020).

Calcium, Magnesium and Sulfate

In this study, concentrations of Ca and Mg were not affected by the addition of SMC. Both elements contain a positive charge making them naturally more attracted to clay and OM particles in the substrate solution (Neilsen and Stevenson 1983, Streich Anne et al. 2014). The increase in CEC to approximately 11.9, 18.1, 20.1, 21.0 (meq/100g) at 0, 2, 4, and 6 cm, respectively, contributed to the substrates ability to retain these cations. This suggests that despite the increase in Ca and Mg facilitated by the addition of SMC, the heighted CEC effectively retained nutrients within the media. S leaching was increased at 2 cm of SMC 12%, and 11% at 7, and 17 DAT and decreased by 7% at 28 DAT. At 4 cm decreases were 14%, 22%, and 16% at 7, 17, and 28 DAT and at 6 cm 6%, 24%, and 23% at 7, 17, and 28 DAT. SMC is known to contain and leach high concentrations of S (Stewart et al. 1997). Sulfur is an anion that is naturally mobile in soil subjecting SMC to increased S leaching. (Lisowska et al. 2023).

Micronutrients dynamics

All micronutrients examined displayed a significant difference in the foliar uptake of nutrients throughout the experimental period. B increased linearly in foliar nutrient uptake in the presence of SMC, due to the additional B added by the SMC and the increased water holding capacity provided by the SMC allowing passive diffusion to occur more easily (Brdar-Jokanović 2020). Zn, Mn Fe, and Cu all showed reductions in foliar uptake in the presence of SMC. These nutrients can all be classified as heavy metals and their reactions in the substrate are primary controlled by sorption, desorption, and dissolution – precipitation reactions (He *et al.* 2006). OM can decrease availability of micronutrients by causing redistribution among their complex fractions (Dhaliwal et al. 2019).OM has been shown to decrease the solubility of Zn specifically by absorbing the surface of functional groups leading to reduced availability and reduced uptake (Dhaliwal et al. 2019).

The amount of leached Mn and Fe were reduced by presence of SMC. There is an indication that reactions between Fe/Mn and P taking place under experimental conditions and maintaining these nutrients in the substrate for longer periods of time. Based on the visual appearance of the experimental zinnias, it is suspected that all micronutrient concentrations in the plants are within sufficient ranges when combining GRM with SMC and CRF.

Conclusion

Despite the decrease in leached NH_4^+, total N leached was not influenced by the addition of SMC. For intensive roof top gardens, a reduction in concentrations of leached N will be more affected by a decrease in applied irrigation, which can be achieved using SMC due to the increase in WHC. This data did provide a roof top gardening practice that can reduce the losses of P through the storm water systems in establishment phases and possibly lead to a decrease in fertility requirements from inorganic fertilizer. Leachate data from this experiment suggests that 4 cm of SMC maximized the reduction of leached P and maximized WHC. It is evident that more research is needed to assess the complex dynamics of GR substrates and the role OM and CRF can play in fertility management. As roof top gardens continue to become more prevalent fertility management recommendations will be critical to optimize crop yields and maintain positive environmental impacts.

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Tables and Figures

Table 2.1 Growth parameters used to determine the effect of spent mushroom compost on zinnia production.

Treatment [w]	Plant height [y]	SPAD	Flowers	Lateral shoots
0	52.47n.s.[z]	33.96n.s.	0.59n.s.	9.70n.s.
2	53.96	33.77	0.63	8.95
4	55.02	33.77	0.64	9.07
6	53.36	33.17	0.57	9.61
P-value	NS	NS	NS	NS

[z] Means with the same letters in a column are not significantly different at (P<0.05) as determined by analysis of variance and lsmeans using GLIMMIX procedure and type III sum of squares in SAS. n.s.=not significant

[y] Plant height was measured in cm.

[x] measurements were repeated and taken on DAT 3, 10, 17, 24, 28.

[w] Treatments are cm of SMC added to containers.

Table 2.2 Average macronutrient uptake (mg) [y] in zinnias.

Treatment [x]	N	P	K	Mg	Ca	S
0	555n.s.[z]	120n.s.	688a	173n.s.	423n.s.	66.8n.s.
2	556	125	770ab	171	459	67.5
4	547	128	808a	178	452	68.8
6	528	123	820a	167	437	63.3
P-value	Ns	Ns	<.0001	Ns	NS	Ns

[Z] Means with the same letters in a column are not significantly different at (P<0.05) as determined by analysis of variance and lsmeans using GLIMMIX procedure and type III sum of squares in SAS. n.s.=not significant

[Y] All values are displayed in mg.

[x] Treatments are cm of spent mushroom compost added to containers.

[w] Total foliar nutrient analysis included shoots, leaves, flowers, and buds only excluding roots.

Table 2.3 Total micronutrient foliar (mg)[y] uptake in zinnias.

Treatment [w]	B	Zn	Mn	Fe	Cu
0	1.94b[z]	1.31a	3.36a	3.02a	0.12a
2	2.29ab	0.96b	1.73b	2.37ab	0.10ab
4	2.44a	0.95b	1.61b	2.32ab	0.11ab
6	2.65a	0.88b	1.38b	2.23b	0.10b
P-value	<.0001	<.0001	<.0001	NS	NS

[Z] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS. Significance at alpha =0.05.

[Y] All values are displayed in mg.

[w] Treatments are cm of spent mushroom compost added to containers.

[v] Total nutrient analysis of the plant included shoots, leaves, flowers, and buds only excluding roots.

Table 2.4 Cumulative macronutrients leached (mg)[x] over 28 days in containers treated with 0, 2, 4, and 6 cm of spent mushroom compost.

Treatment [y]	NH^{4+}	NO_3^-	P	K	Ca	Mg	S
0 cm	29.0n.s.[w]	79.2n.s.	36.1a	78.7c	149n.s.	45.7	287b
2 cm	24.2	71.3	27.3b	112bc	156	41.2	335ab
4 cm	24.2	67.4	25.9b	136ab	161	42.7	356a
6 cm	24.2	78.7	28.8b	175a	164	43.4	389a
Significance	Ns	Ns	<.0001	<.0001	Ns	Ns	<.0001

[z] Values are determined by cumulative mg of nutrient in leachate between each treatment.

[y] Treatments are cm of spent mushroom compost added to containers.

[x] All values are expressed in mg

[w] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS. Significance at alpha =0.05. n.s.= not significance

Table 2.5 Average of macronutrients (mg) leached over 28 days in containers treated with 0 cm, 2, 4, and 6 cm of spent mushroom compost.

Treatment[w]	NH^{4+}	NO_3^-	P	K	Ca	Mg	S
0 cm	19.1a[z]	407n.s[z]	31.2a	444d	923n.s	147n.s.	2170c
2 cm	5.26b	373	20.2b	750c	931	139	2449bc
4 cm	3.96b	316	13.7c	912b	927	130	2604ab
6 cm	4.64b	377	20.7b	1140a	942	133	2740a
Significance	<.0001	NS	<.0001	<.0001	NS	NS	0.0019

[Z] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS. Means with the same letters in a column are not significantly different at (P<0.05). n.s= not significant

[Y] Values are determined by water samples taken from leachate capture system (DAT 7, 17, 28).

[X] All values are represented in mg.

[w] treatments are cm of spent mushroom compost added to containers.

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Table 2.6 Average of micronutrients (mg)[x] leached over 28 days in containers treated with 0, 2, 4, and 6 cm of spent mushroom compost.

Treatment [v]	B	Cu	Fe	Mn	Zn
0 cm	2.21c[z]	0.334n.s.[z]	14.7a	1.7a	0.868
2 cm	2.60bc	0.307	8.86b	0.46b	0.884
4 cm	2.84ab	0.344	9.60b	0.39b	0.845
6 cm	3.13a	0.368	10.6b	0.37b	0.888
Significance	<.0001	NS	<.0001	0.0002	NS

[Z] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS Means with the same letters in a column are not significantly different at (P<0.05). n.s= not significant

[Y] Values are determined by water samples taken from leachate capture system (DAT 7, 17, 28).

[X] All values are represented in mg.

[v] treatments are cm of spent mushroom compost added to containers.

Figure 1. Leachate capture system used to capture all water through the system.

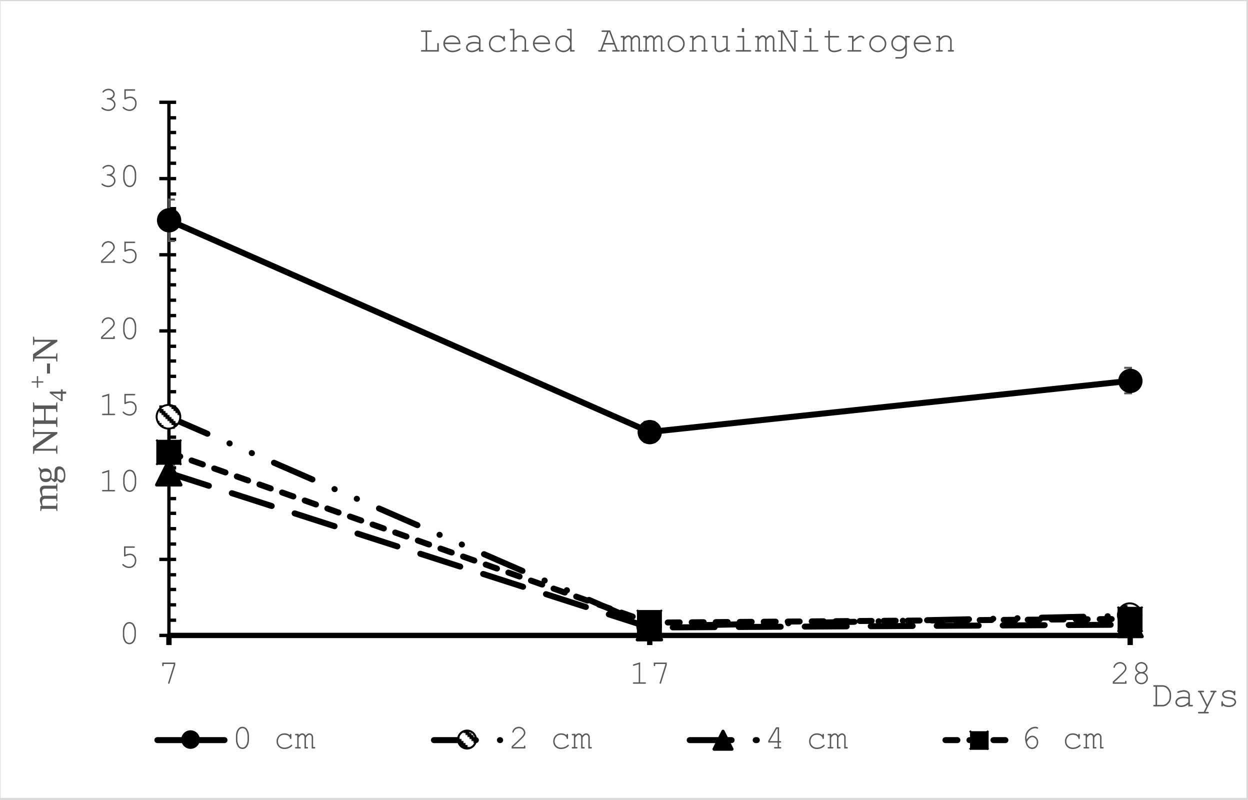

Figure 2. Decrease in leached ammonium nitrogen (mg) in green roof media treated with 0, 2, 4, and 6 cm of treated with spent mushroom compost.

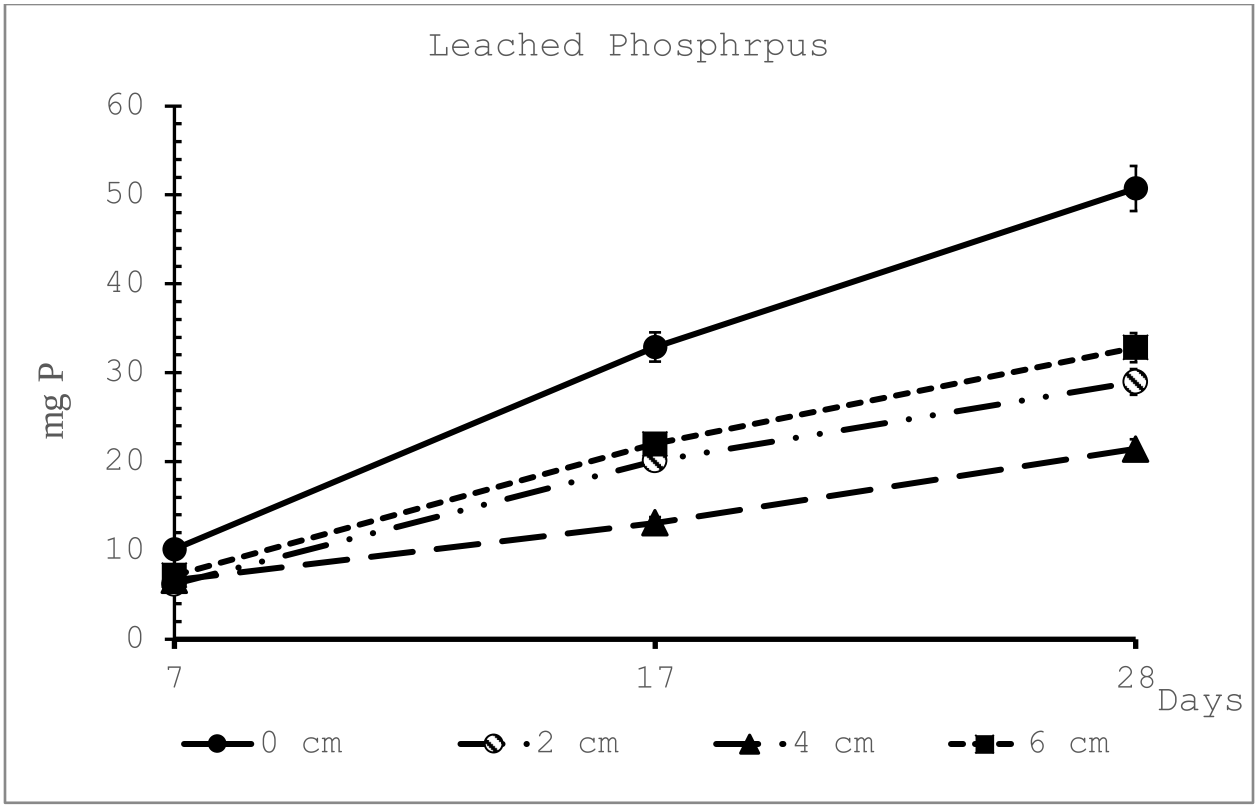

Figure 3. Decrease in leached phosphorus (mg) in green roof media treated with 0, 2, 4, and 6 cm of spent mushroom compost.

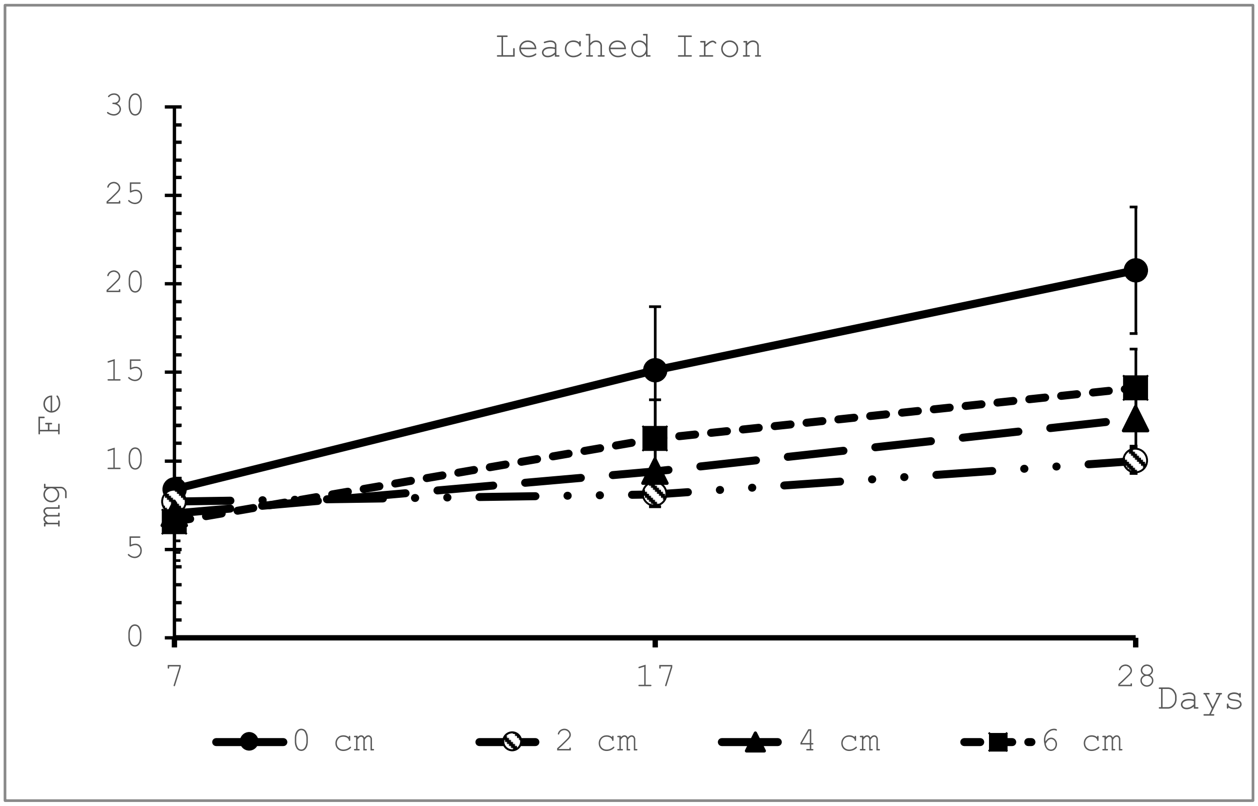

Figure 4. Decrease in leached Iron (mg) in green roof media treated with 0, 2, 4, and 6 cm of spent mushroom compost.

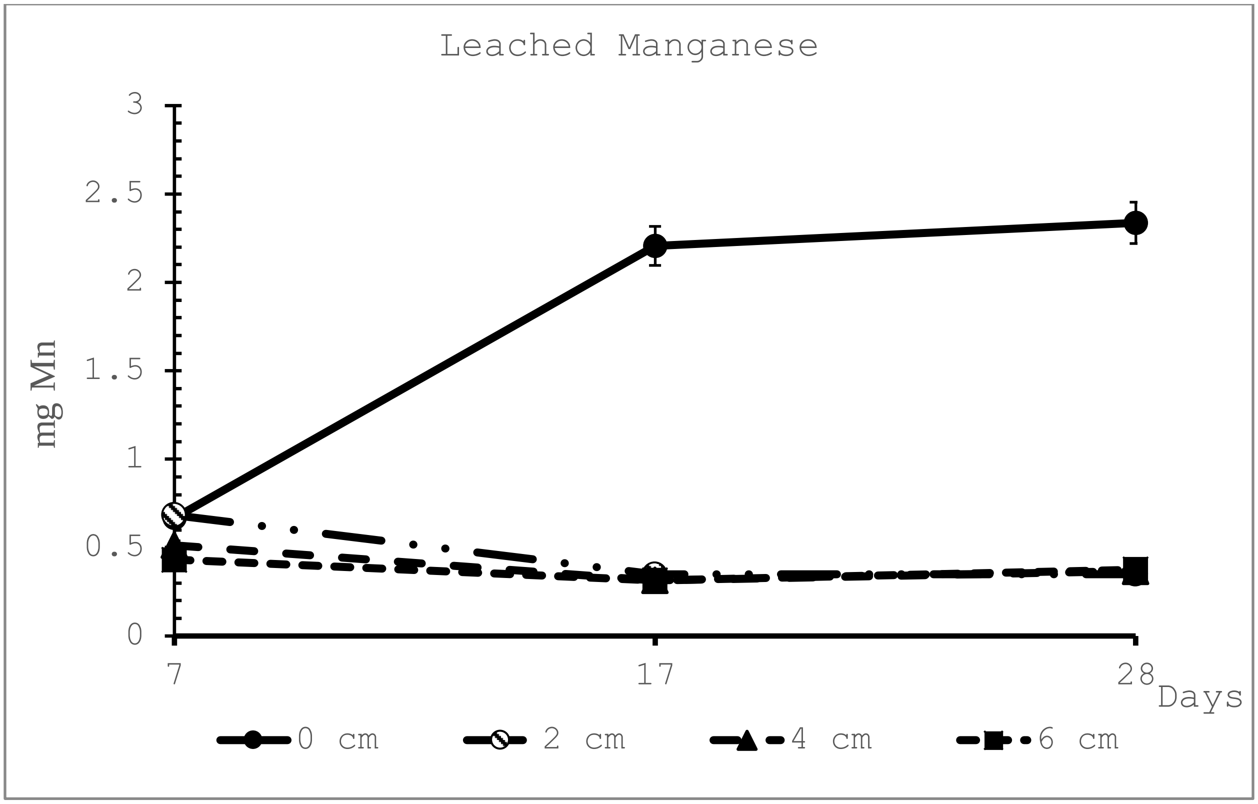

Figure 5. Decrease in leached manganese (mg) in green roof media treated with 0, 2, 4, and 6 cm of spent mushroom compost.

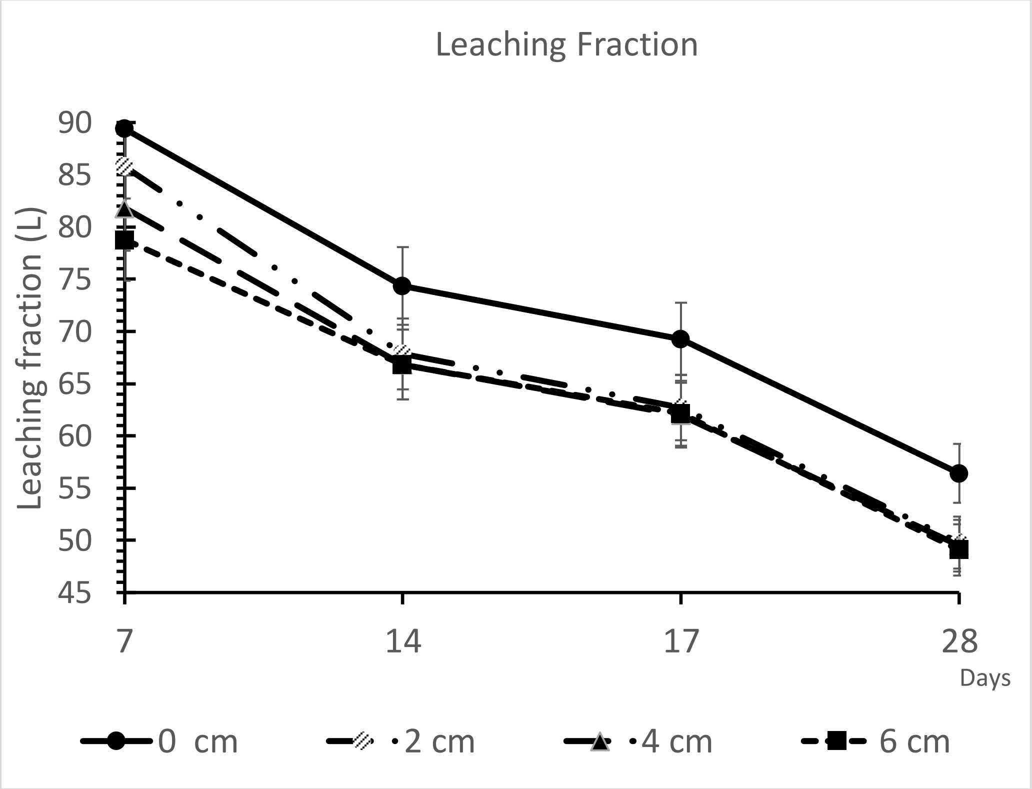

Figure 6. Decreased leaching fraction of municipal water in green roof media with 0, 2, 4, and 6 cm of spent mushroom compost as an organic matter source.

Appendix 1

Substrates, including root mass, from the experimental units that were used to collect leachate throughout the experiment, were dried in a forced-air drier and a sample from each substrate was analyzed for nutrient concentrations of Nitrogen, Nitrate-N, Potassium, Phosphorus, Magnesium, Calcium, Sulfur, Boron, Zinc, Manganese, Iron, and Copper. Nitrogen and nitrate-N were analyzed using the Kjeldahl (KjN) method. and all other elements were extracted using a Mehlich-I extract and analyzed via ICP (Waters Agricultural Laboratory, Camilla, GA).

The substrate analysis resulted in a high variation in the data. The sampling method for this specific experiment could have been the cause of error. Samples were analyzed using a melich 1 extraction, but FLL has developed a standard methodology used for determining chemical characteristics of green roof substrates (FLL 2018). Kong et al, used this method outlined by the FLL coupled with a saturated media extract method that is currently the method of testing soilless greenhouse media and green roof substrates both in the United States and internationally (Kong et al. 2015). Melich 1 extraction makes an assumption of the density of a sample usually ranging from 1 to 1.2 g/cm^3 , and to present test results on an acre basis an additional assumption is required on the quantity of soil in an acre-furrow slice which is commonly assumed to be 2 million pounds (University of Kentucky *et al.* 2005). The bulk density of rooflite intensive ag (Skyland USA, LLC) is 0.65 g/cm^3 (Kong et al. 2015). This deviation of the bulk density is the probable cause of the higher standard deviation in the resulting media.

Table 2.7 Average substrate availability of macronutrients (mg)[x] on day 28 in containers treated with 0, 2, 4, and 6 cm of spent mushroom compost.

Treatment	N	P	K	Ca	Mg	S
0 cm	47.7	105	222	1230c[w]	66.4c	7.18
2 cm	63.6	142	294	2620b	125b	2.68
4 cm	40.0	136	206	3320a	164a	5.03
6 cm	44.7	141	210	2980ab	144ab	7.26
P-value	NS	NS	NS	<.0001	<.0001	NS

[Z] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS. Significance at alpha =0.05.

[Y] Values are determined by the final substrate analysis that includes media, spent mushroom compost and zinnia roots.

[X] Values are represented in mg.

[w] Means with the same letters in a column are not significantly different at (P<0.05).

[v] treatments are cm of spent mushroom compost added to containers.

[u] substrate samples were taken from 12 subsamples (n=24)

Table 2.8 Average substrate availability of macronutrients (lbs/acre)[x] on day 28 in containers treated with 0, 2, 4, and 6 cm of spent mushroom compost.

Treatment [v]	N	P	K	Ca	Mg	S
0 cm	52.4	283	592	3430c	197b	25.1
2 cm	64.1	340	661	6640b	332a	9.00
4 cm	35.8	305	441	7600a	386a	12.0
6 cm	45.1	350	493	7490ab	391a	18.7
P-value	NS	NS	NS	<.0001	<.0001	NS

[Z] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS. Significance at alpha =0.05.

[Y] Values are determined by the final substrate analysis that includes media, spent mushroom compost and zinnia roots.

[X] Values are represented in lbs/acre.

[w] Means with the same letters in a column are not significantly different at (P<0.05).

[v] treatments are cm of spent mushroom compost added to containers.

[u] Substrate samples were taken from 12 subsamples (n=24)

Table 2.9 Average substrate availability of micronutrients (mg)^{x} on day 28.

Treatments^{v}	B	Fe	Cu	Mn	Zn
0 cm	0.314c^{w}	44.6a	2.80	25.6a	9.27a
2 cm	0.503b	24.6b	0.690	23.9ab	7.44ab
4 cm	0.607ab	18.1bc	0.560	24.0ab	8.62a
6 cm	0.640a	16.3c	0.436	16.7b	6.12b
P-value	<.0001	<.0001	<.0001	<.0161	0.0027

[Z] Significance was established with an analysis of variance using GLIMMIX procedure and type III sum of squares in SAS. Significance at alpha =0.05.

[Y] Values are determined by the final substrate analysis that includes media, spent mushroom compost and zinnia roots.

[X] Values are represented in mg.

[w] Means with the same letters in a column are not significantly different at (P<0.05).

[v] treatments are cm of spent mushroom compost added to containers.

[u] Substrate samples were only taken from 12 subsamples (n=24)

Literature

Kong, A. Y. Y., Rosenzweig, C., & Arky, J. (2015). Nitrogen Dynamics Associated with Organic and Inorganic Inputs to Substrate Commonly Used on Rooftop Farms. In *HORTSCIENCE* (Vol. 50, Issue 6).

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