Testing the Stormwater Infiltration of Different Compost Blends in a Bioretention System

By

Stephen D. Olson

A Master's Project submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Environmental Assessment

Master of Environmental Assessment

Raleigh, North Carolina
2021

APPROVED BY:

Jennifer Richmond-Bryant
Committee Chair

ABSTRACT

OLSON, STEPHEN. Testing the Stormwater Infiltration of different Compost blends in a Bioretention system. (Under the direction of Dr. Jennifer Richmond-Bryant, North Carolina State University).

Infiltration of rainwater in different compost blends was studied using a contained experiment. Stormwater runoff is problematic on many college campuses, especially those that have grown substantially in size and number of buildings. Traditional stormwater infrastructure often cannot handle the amount of runoff, leading to erosion, flooding, and build-up of contaminants. Several bioretention systems have been studied and utilized successfully on college campuses to help mitigate this issue. Use of compost as the primary medium in a bioretention system was tested in this study based on a need expressed by UNC Charlotte's Facilities Management Office. Bioretention test cells were built using wood, PVC, and plastic tubs and buckets. Compost amendments were obtained from various sources and were tested over the course of 4 weeks with twice weekly artificial rain events ranging from 0.5 inches to 2 inches. Results indicated a positive relationship between infiltration and moisture content of each compost amendment and a negative relationship between infiltration and organic material content of each compost amendment. It is recommended that UNC Charlotte consider using in-vessel and aerated static compost as a primary substrate for bioretention systems based on the infiltration data and cost. Further studies are recommended to test for compaction of soil over time, different variation of compost, and cross-examination with different plants within the system.

BIOGRAPHY

Stephen Olson currently works for UNC Charlotte as the Cybersecurity Workforce Certificate Coordinator. He formerly worked as the Recycling & Waste Reduction Coordinator in Facilities Management. He graduated from Brevard College in Brevard, North Carolina with a Bachelor of Science in Environmental Science. Stephen taught Earth Science at West Charlotte High School in Charlotte, NC for two years prior to attending graduate school at North Carolina State University. He served 8 years in the United States Army and Army Reserve. He is married to his lovely wife, Sophia, who is an Art Teacher in Charlotte, NC. They have one dog, Pontiac, and a cat, Tesla.

ACKNOWLEDGMENTS

I thank Dr. Jennifer Richmond-Bryant (North Carolina State University) and Ms. Linda Taylor (North Carolina State University) for providing support throughout the completion of this project. I thank Mr. Greg Cole (UNC Charlotte), Mr. Peter Franz (UNC Charlotte), and Ms. Emily Herring (UNC Charlotte) for providing insight on valuable information pertinent to this project. I thank AmeriCorps for funding my graduate degree. I thank Dr. Aziz Amoozegar (North Carolina State University) and Ms. Christina Kranz (North Carolina State University) for assisting me in formulating my project. I thank Ms. Shannon Caveny-Cox (UNC Charlotte), my supervisor, who supported me fully in completion of this project. Most importantly, I thank my wife, Sophia, and family for moral support and encouragement throughout my degree. This work was supported by a grant from the Charlotte Green Initiative, a student-led group at UNC Charlotte that focuses on sustainability and research.

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Introduction

Stormwater Runoff is problematic on the campus of UNC Charlotte. The university was founded in 1946 initially as a school for returning World War II veterans, focusing primarily on medicine and business[1]. The University started with only 278 students and has grown to an enrollment of nearly 30,000 full-time students. Therefore, it continues to construct more buildings. The main campus sits on nearly 1,000 acres about ten miles northeast of Charlotte's downtown area and is completely self-contained[2]. The campus currently has 33 administrative buildings and 18 residence halls. Two new buildings are currently under construction.

Most of the campus does not currently sit inside of a flood zone, but some sections along Toby Creek, which flows into Mallard Creek, have potential for flooding at least once per year[3]. Although it is not in a flood zone designated by the National Pollutant Discharge Elimination System (NCDES), there are localized stormwater management issues in certain sections of campus. Currently, the City of Charlotte, in conjunction with UNC Charlotte, is conducting a large-scale restoration project of Toby creek to restore watershed function[4].

On campus, there is existing stormwater infrastructure in place, including underground drainage tunnels. Most buildings, except for several older residence halls, have roof-fed gutters that lead directly into the drainage system connected to the City of Charlotte's stormwater infrastructure[5]. UNC Charlotte is currently not in compliance with the City of Charlotte's Stormwater Ordinance, Article IV of Chapter 18 of the Post-Construction Stormwater Ordinance Act[5].

Currently, there are several stormwater management systems on campus, including three rain gardens, one underground detention pond, one sand filter, and two above-ground retention ponds. All are situated near the EPIC building on campus in the Research Institute[6]. However, the rain gardens that were previously established were done so through one academic program via graduate work and were not consistently maintained after they were established. Maintenance problems included blockage in the inlet/outlet system, death of perennial plants, and the use of annual plants that were not re-planted.

Bioretention gardens, in addition to several other stormwater management systems, have been used across the globe in a variety of settings. Bioretention gardens installed on the campus of The University of Technology in China were shown to reduce flooding by 60-70% in the highest problem areas[8]. Rain gardens can remove pollutants and nutrients from stormwater and aid in preventing entrance into existing stormwater infrastructure[6]. When installed properly, they remove suspended solids, of which many are taken up by vegetation[9]. Forb-rich perennials are an effective option when planted inside a rain garden, as their root structure grows quickly, and though small, can be planted in high densities. Daylilies, clovers, and sunflowers are also viable options, given their ability to be planted densely and to take in considerable amounts of moisture and nutrients[10].

Studies have provided evidence for the efficacy of tall grasses to properly manage stormwater infiltration[11,12]. The root structure and general porosity of perennial, forb-rich grasses provide many benefits within a small area. Larger shrubs and trees can be suitable for bioretention gardens based on their high evaporation characteristics, but they still absorb less water needed for their root systems given their smaller surface area compared with smaller shrubs[11]. The efficacy of rain gardens has been studied in different cities in the world, and variability has been noted based on the specific types of soil used. In some cases, there were negative effects not related to stormwater management when choosing specific soils, such as those that are known as being hotspots for mosquito larvae[12.]

Universities and municipalities have adopted a variety of bioretention methods, including vertical gardens to mitigate stormwater via existing roof-fed downspout and gutter systems. These can be not only aesthetically pleasing, but also help to absorb sound[13]. In an experiment conducted in Canada, ten different bioretention gardens were tested for their ability to remove phosphorus and nitrogen[14]. All test bioretention cells were built above ground to best analyze drainage and to sample the water to determine removal efficiency. Though they were placed in large rain barrels, the results still showed that a sandy/soil mix is the most efficient at removing nitrogen and phosphorous[14].

It has been shown that the use of waterproof cloths, in conjunction with PVC perforated tubing and gravel, can help to collect runoff without adversely impacting groundwater through pollutant infiltration[11]. A similar setup could be helpful in managing overflow, inflow, and allow proper confluence of suspended solids. Proper uptake of nutrients in a bioretention system like this would allow for positive vegetative growth[15].

Invertebrate populations have been quantified to study the efficacy of rain gardens[25]. Invertebrates can be used to determine soil quality, because they are indicators of positive nutrient flow. As organisms decompose in the gardens, this can create a more nutrient rich soil media, which helps to promote the growth of the fauna and flora chosen for the system. On the other hand, it was noted that invertebrate decomposition can become a problem as well, because soils that are well-chosen for stormwater retention could also be too rich of a habitat for living invertebrates, thus creating a population issue[16].

Previously, UNC Charlotte hired a consulting firm to make general recommendations to improve stormwater management on campus. Their report included generalized proposals for green roofs, functional landscaping, outfall treatments, and bioswale conveyances[6]. The report also identified multiple areas that fall under these categories, including areas that the United States Environmental Protection Agency considered to be problematic areas regarding localized flooding[7].

After consultation with stormwater professionals and landscape architects on campus, in addition to budget constraints resulting from the COVID-19 pandemic, it has been recommended that more studies be conducted prior to the construction of any new bioretention infrastructure[17]. Additionally, any proposed bioretention systems need to be preferably cost-efficient and sustainable. A bioretention system that is self-sufficient would be preferable to the staff members at UNC Charlotte, using materials that are available and generated on campus. A low-cost system, minimizing utilization of transportation, management, and staff, would be better accepted by campus leadership. An experiment was designed to test for efficacy of different variables related to compost used in bioretention gardens, with the objective of determining the most effective compost for optimizing infiltration in bioretention gardens. This objective will be tested via controlled rain events, which will be detailed further.

Methods

This study was conducted in coordination with UNC Charlotte's Stormwater Management Department and Landscape Architecture Department to study best practices for bioretention systems. UNC Charlotte has grappled with the need for large-scale construction projects in the past decade, with little to no improvements on stormwater infrastructure. There are several areas on campus that could possibly benefit from the installation of bioretention systems.

UNC Charlotte is a public university situated northeast of Charlotte, NC. There are currently two campuses, including a Center City Campus in downtown Charlotte and a Main Campus in what is referred to as University City. This Main Campus sits on 955 acres of land between Route 29 and NC Hwy 49, 9 miles north of Charlotte[17]. Charlotte averages approximately 43 inches of rain between 2000-2015, but in recent years, has seen that total nearly double to 78 inches in 2020. Months with the highest average rainfall include April, May, June, and July, ranging from 1.5 inches to 2 inches of rain monthly. Additionally, the average amount of rainfall days in April through July ranging from 13 to 17 days[21].

Experimental design for this study will be based on a previous paper by Randall that tested 10 bioretention mesocosms, or cells, using a simple wooden structure that contained each cell[14]. Each cell in the Randall[14] study had a different combination of vegetation, including sea thrift, daylilies, and wormwood. Soils were mixtures of gravel, sand, and compost, but the study focused primarily on root structure and the efficacy of those plants in removing suspended solids. Gravel, sand, and compost were tested in differing proportions, ranging from 30%-50% of each compound, respectively.

The experiment conducted in this study was modeled after the Randall[14] experiment but focused primarily on soil variation and types of compost. The waste industry has grappled with the large amount of compostable products that are left within the landfill stream[18]. Routine waste audits at UNC Charlotte found that approximately 54% of all waste was compostable, offering an area of opportunity for the use of different compost blends on campus in bioretention systems[19]. Reuse of compost would simultaneously offer benefits for both the waste stream and stormwater infrastructure.

This experiment was focused mainly on the ability of different soil and compost media’s ability to retain rainwater. We tested the following compost blends, making up 100% of the total media in each bioretention cell (Table 1).

1. Aerated windrow compost blend generated at UNC Charlotte
2. Aerated static compost generated at the Botanical Gardens at UNC Charlotte
3. In-vessel compost from UNC Charlotte’s older compost silos
4. Manure blend purchased from local home improvement store

5. Peat humus blend purchased from local farm store

Compost Blend	% Moisture	% Air	% Organic Material	%Inorganic Material
Aerated compost	40	5	40	15
Aerated static compost (leaves)	25	15	50	10
In-vessel compost	40	5	50	5
Manure blend	75	5	15	5
Peat Moss blend	25	10	60	5

Table 1. Content make-up is shown for each of the compost blends. All percentages are estimates.

A covered space was used for this experiment inside of a carport at a private residence in the Charlotte area. Due to COVID-19 precautions during the time of this study, conducting the experiment on the campus of UNC Charlotte was not feasible. This 25 x 40 foot concrete and brick enclosure was suitable for keeping the experiment away from the elements, which prevented actual rain events from compromising the data.

Figure 1. Bioretention test cell layout.

The enclosure was used to create artificial rain events using measured amounts of water, and a scaffolded, multi-tier system was built to retain the mesocosm containers using 2 x 4 boards, nails, and schedule 40 1.5 inch PVC piping to allow for inlet and outlet fixtures. 10 different bioretention cells were placed in a 10 x 30 foot structure. 2x4 pressure-treated pine beams were used to construct the initial frame using 8 beams.

Rain events were simulated twice per week with quantities of 0.5 in, 1.0 in, 1.5 in, and 2.0 in. The order of the rain events was chosen at random using the random number generator from

Microsoft Excel (v15.0), with a maximum of 2.0 inches of rain for any one event. The rain event schedule is shown in Table 2.

The rain events were measured using 10-gallon buckets (Figure 2). Since buckets chosen for each cell are the same volume and area as those used for each bioretention cell, no further calculation is needed.

	Week 1	Week 2	Week 3	Week 4
Rain Event 1	0.5 inches	1.5 inches	0.5 inches	1.0 inches
Rain Event 2	2.0 inches	1.0 inches	0.5 inches	1.5 inches
Days of Week	Wed, Fri	Thur, Fri	Mon, Wed	Wed, Tue

Table 2. Schedule of artificial rain events.

Capture chambers were built out of schedule 40 PVC piping and blue 5 gallon measuring buckets placed below each mesocosm (Figure 3). These capture chambers allow for the measurement of rainwater that infiltrates the system and is not captured by the soil, rock, or root structure media.

Figure 2. Outlet chamber in bottom of bioretention cell is shown.

Data were collected by observing the outlet chambers that are connected to each bioretention cell. Infiltration was measured in the outlet chambers using measuring tape attached to the side of each chamber. Each chamber can hold up to 5 gallons of water. Data were collected for each rain event over the course of 5 weeks, with a total of 10 observed rain events. Rain events were randomized to mimic real conditions because weather varies.

Data were collected on each day of the experiment, noting the amount of rainwater that had infiltrated through each bioretention cell and made its way into the outlet chamber. These data were collected once on the night of the artificial rain event at 9 pm. Data were collected cumulatively so that the amount of total infiltration would be measured over the course of the entire study. To mimic the conditions in a bioretention system, rainwater would not be removed after each rain event. Instead, cumulative rainwater was measured over the duration of the experiments. Infiltration per event was then calculated at the end of each event, with the cumulative rainfall subtracted from the most recent event. Infiltration was measured in outlet chambers via measuring tape affixed to the inside of the chamber six hours after rainfall event.

Results

Infiltration was much higher in compost blends that began with higher moisture content, as was seen primarily in the Manure Blend which was made primarily of manure purchased from a local

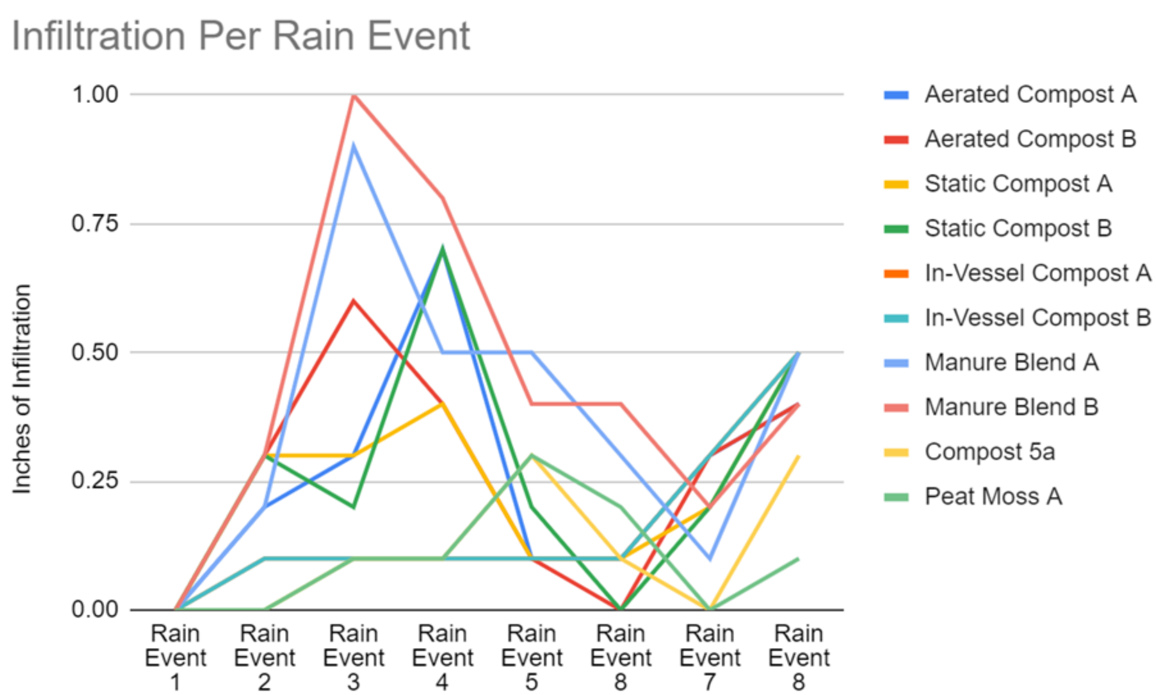

Figure 3. Infiltration is shown for each of the 10 compost blends according to each of the 8 artificial rain events.

home improvement store. The second highest amount of infiltration came from Compost 1, which was composed of aerated windrow compost. Infiltration rates were highest in the Manure Blend cells, followed by the Aerated and Static Compost Blends. Peat Moss and In-vessel Compost Blends had the lowest infiltration rates cumulatively and consistently less infiltration per artificial rain event.

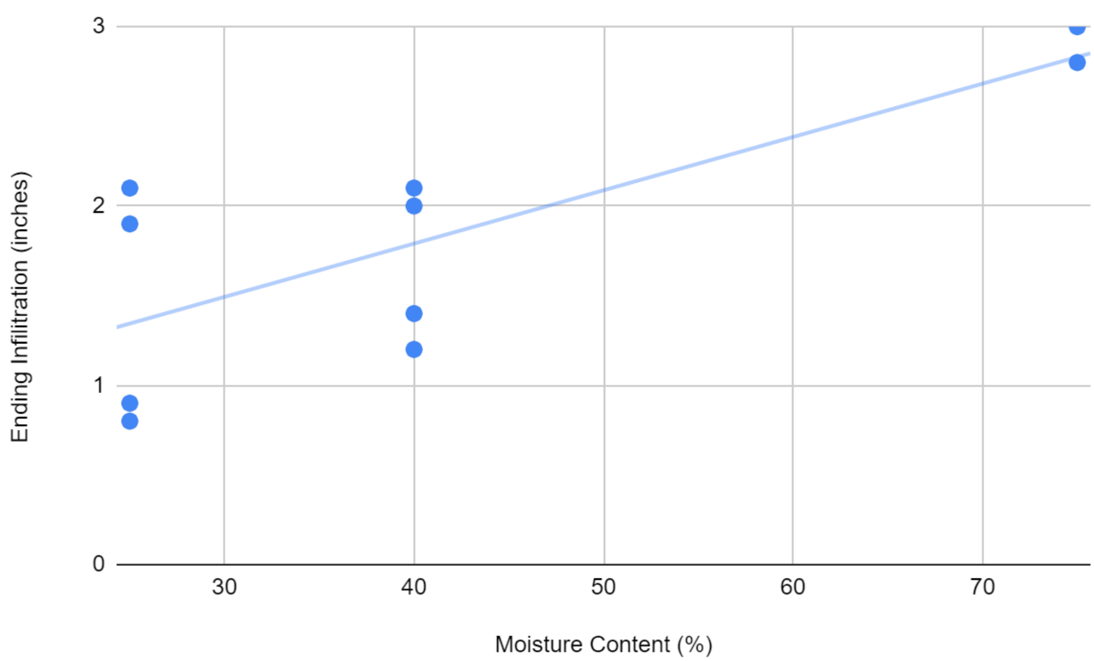

Figure 4. Ending infiltration (in inches) is shown according to moisture content present in each compost blend.

Infiltration was found to be higher when moisture content of the original substrate was higher (Figure 4). The Manure Blend, for example, showed the highest amounts of infiltration at nearly 3 inches overall, with a starting moisture of approximately 75%. On the lower end, the Aerated Static Compost and the Peat Moss Blend showed the lowest amounts of infiltration and had moisture contents of approximately 25%. Based on these data, higher moisture contents show a positive relationship with higher infiltration rates. Data were normalized and re-plotted; trends were similiar, but slope and R^2 were different. (See Figure A1 in the Appendix). R^2 value was calculated at 0.591 for the raw data, and 0.788 for the normalized data. A positive relationship between moisture content and infiltration is shown in both raw and normalized figures.

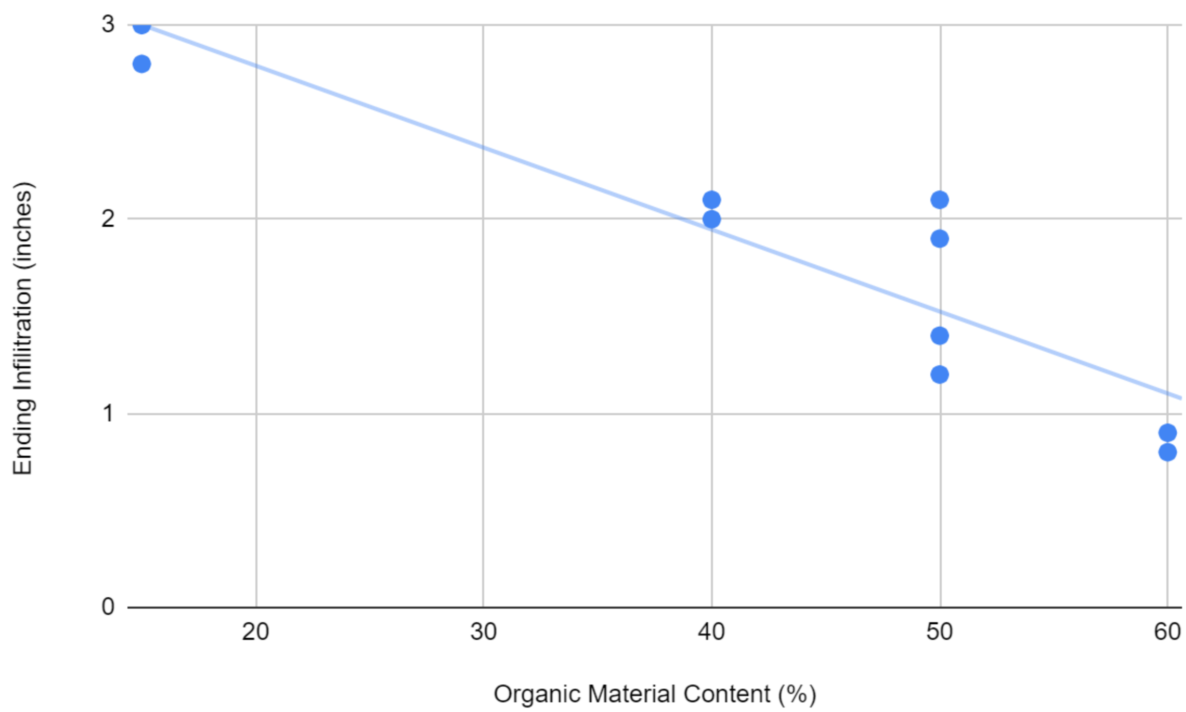

Figure 5. Ending infiltration (in inches) is shown according to organic material content present in each compost blend.

In Figure 5, we see that organic matter has a negative relationship with infiltration rates. The Peat Moss Blend had the lowest infiltration of all compost blends, with an organic content of approximately 60%. Data were normalized by the amount of rainfall per event and re-plotted; trends were similar with those seen for total infiltration, though slope and R^2 were different (See Figure A2 in the Appendix). The R^2 for the raw data was 0.841 and 0.108 for the normalized data, respectively. An inverse relationship between organic material content and infiltration were shown in both raw and normalized figures.

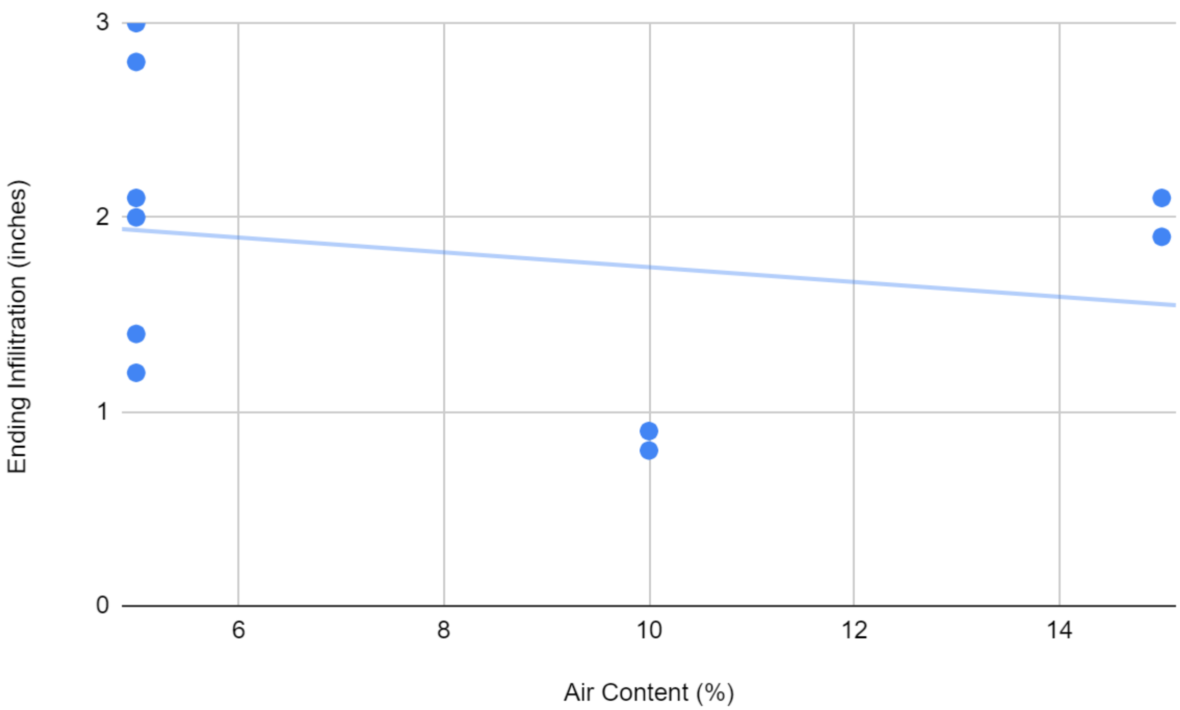

Figure 6. Ending infiltration (in inches) is shown according to air content present in each compost blend.

There is low correlation between the amount of air present in the compost and infiltration (Figure 6). The percentage of air present in each blend did not vary significantly, ranging from 5% to 15%. Data were normalized and re-plotted; trends were similar, but with different slope and R^2 (See Figure A3 in the Appendix). R^2 for the raw data was 0.41, while for the normalized data was 0.004.

Annual cost estimations for each compost blend vary. These are an important factor in deciding which substrate is not only most effective at limiting infiltration but is also economically feasible. The following information offers cost estimates for using each compost blend variation based on square footage.

Manure Compost Blend	$5.23
Peat Moss Blend	$3.99
Aerated compost blend	Free to $6.50
Botanical Gardens blend	Free to $2.00
In-vessel compost blend	$7.50

Table 3. Cost estimation for each type of compost amendment. All prices are shown per cubic foot.

These estimations are based on current prices at a local hardware store[21], and estimated costs developed by UNC Charlotte's Office of Recycling & Waste Reduction[22].

Discussion

This study was developed from the need for creative and cost-efficient ways to limit the amount of stormwater runoff that adversely impacts the campus of UNC Charlotte and to see if there are sustainable methods to accomplish this. Conclusions from this study could be used for other campuses or municipalities that are looking for more information on the use of compost in bioretention cells. Based upon the data in this study, the In-vessel Compound and the Peat Moss Blend showed the greatest ability to retain stormwater, limiting the amount that will lead to erosion, flooding, and overflow of stormwater infrastructure.

Lower infiltration of the Peat Moss Blend and the In-vessel Compost Blend would, at first glance, be positive for bioretention system usage due to increased stormwater retention. However, it has been shown that low infiltration can lead to less-nutrient dense soil, and tillage in combination with compost amendments, can lead to reduction in absorbing stormwater runoff[26]. This, in part, is due to large levels of compaction in areas that receive large amounts of precipitation[26]. Compaction can lead to a host of adverse effects for a bioretention system and can ultimately reduce the infiltration of rainwater[30]. Once systems reach this level of compaction, it can be difficult to remediate to a level of efficiency seen prior[31].

Moisture content of original compost blends was varied, ranging from 25% for the aerated static compost to 75% for the manure blend. A relationship was observed between higher moisture content and higher infiltration, which may be explained by moisture-holding capacity being lower for amendments that begin with higher moisture content[27]. Manures, for example, will generally have increasingly lower permeability as moisture contents increase. This, in turn, can cause surface level flooding due to the manure reaching a level of saturation that no longer allows for the flow of water through the system[29].

There was little variation in infiltration rates vs. air content in this study across all compost variations. However, air content only ranged from 5-15% in the original compost blends. It has been shown, however, that infiltration rates can decrease with a reduction in porosity, namely from higher air content in certain soils[27]. Generally, air content and air porosity have a negative relationship with saturation[31]. However, in this study, there is not enough evidence to gather additional information due to the low range in air content.

Organic material content that was higher in compost blends was associated with lower infiltration rates. There is evidence that more organic media within a bioretention system can increase the amount of positively charged elements a soil can hold and subsequently increase its ability to allow for more infiltration[28.]

This study's experimental design was loosely based on a previous study that built bioretention cells in a similar fashion. The Randall study mainly focused on the ability for each cell to remove phosphorous and nitrogen[14]. However, findings in this study noted that higher rates of phosphorous and nitrogen removal were associated with using a blend mostly comprised of sand, clay and silt, making up nearly 95% of the system. It was noted that infiltration was still higher in Randall's test, but nutrient removal was achieved[14]. A future study that combines the findings of our study, based on infiltration in relation to moisture content, air, organic material, and types of compost, and those that focus on nutrient removal would be beneficial to gaining a better understanding of how these variables interact.

Though some costs associated with using each compost blend in a bioretention system are difficult to estimate, it is worth noting that in-vessel compost is more expensive based upon the equipment necessary to create it[33]. Though it does limit stormwater runoff and retains water better than others in this study, apart from peat moss, it is the most expensive. Peat moss, which had the lowest infiltration rates, is relatively inexpensive at about half the cost. Certain types of compost, like the static blends used in this experiment, can cost significantly less money considering the environment is naturally plentiful in excess soil, leaves, and miscellaneous organic waste. However, based on infiltration data alone, it may be worth investing in higher quality compost for bioretention systems. Certain university campuses may have existing infrastructure to facilitate large-scale composting, which would aid in the economic and logistic feasibility of using it for bioretention gardens or other systems.

There were several errors and uncertainties present in this study, including the inconsistency of measuring water prior to the manufactured rain events. Though the purpose of manufactured events was to contain the amount of precipitation going through each bioretention test cell, the large amount of water used was not measured precisely, due to manual reading of the 1-gallon and 5-gallon levels of jugs and of the measuring tape. There was also variation in the location where water was poured over each bioretention cell and the distance water was held away from each cell when the artificial rain events were occurring. This variable was not realized until the study was conducted. Further studies on compost variations in bioretention cells should consider standardized methods for measuring infiltration and for releasing measured water into each cell to allow for consistency.

Rainfall amounts within the outlet chambers were not removed in between each artificial rain event. Though this was in part due to a desire for the methodology to mimic actual events, it does lead to the possibility of losses due to evaporation. The amount of evaporation is unknown but may be more pronounced given that this study was done above ground, and infiltrated water was exposed to air. Future studies would be helpful in examining which approach is most effective in determining cumulative infiltration.

By splitting the cells into different sections to examine moisture content, organic and inorganic material, and air, we developed a better understanding of not only these five compost blends, but also some of the variables that have been shown to limit infiltration.. Ideally, a compost blend used in a bioretention system would include a mix of those that offer moderate infiltration, to limit the amount of runoff entering existing infrastructure or flooding the surrounding area[34]. Moderate infiltration may, on the other hand, prevent too much saturation from occurring, and could be ideal for plant health. This, in part, is due to the relationship between hydrologic peak flow and infiltration[36].However, any vegetation that is planned for use in a bioretention system should be chosen carefully in coordination with compost and soil amendments to ensure drainage characteristics are favorable for its root structure[35]. Since tree and shrub roots also have the potential to increase infiltration rates, it is recommended that more studies be conducted to gather evidence on the most suitable vegetation for a bioretention system that primarily uses compost as a substrate[32].

Strengths of this study included control of the input conditions (i.e., rain events), mainly by keeping the experiment under a covered space where local precipitation would not affect the experiments. Additionally, it was ensured that there were two variations of each compost blend, which increased the strength of the data. By utilizing a mixture of commercial and local amendments, it allowed for more pertinent data to inform local leaders. This includes the campus officials who recommended this study be completed, on stormwater management. Lastly, the randomness of rainfall amounts allowed for more realistic application, because weather is variable and inconsistent.

Conclusion

Given the cost estimations and infiltration data present in this study, it is recommended that UNC Charlotte construct bioretention systems using Aerated Static Compost Blends and In-vessel Compost Blends that can be obtained on-site at the University. Though peat moss offered the lowest rates of infiltration, it is recommended to use amendments such as the Static Compost or In-vessel Compost Blends that offer moderate amounts of infiltration based on the literature. In addition, use of compost blends that can be generated on site opens a host of additional benefits to the campus environment. Compost has the potential to greatly reduce the food waste that is sent to the landfill, prevent food waste from infiltrating the wastewater system, and saves additional costs on dumpster collections.

Though education is at the forefront of most waste reduction, bioretention systems that utilize “in-house” compost have the potential to positively assist in the control of stormwater and educate the university community on the importance of sustainable practices. These systems can be more aesthetically pleasing than traditional stormwater infrastructure, can remove sediment loads and pollutants, and often require little maintenance.

With the use of the results in this study, stormwater professionals at UNC Charlotte and landscape architects can decide whether to move forward with additional bioretention systems, possibly using more compost amendments to limit stormwater runoff and assist in overall waste reduction on campus. Ideally, the university and its respective private partners can work together to return to compliance with the City of Charlotte and continue to advance sustainability in overall stormwater management.

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APPENDIX

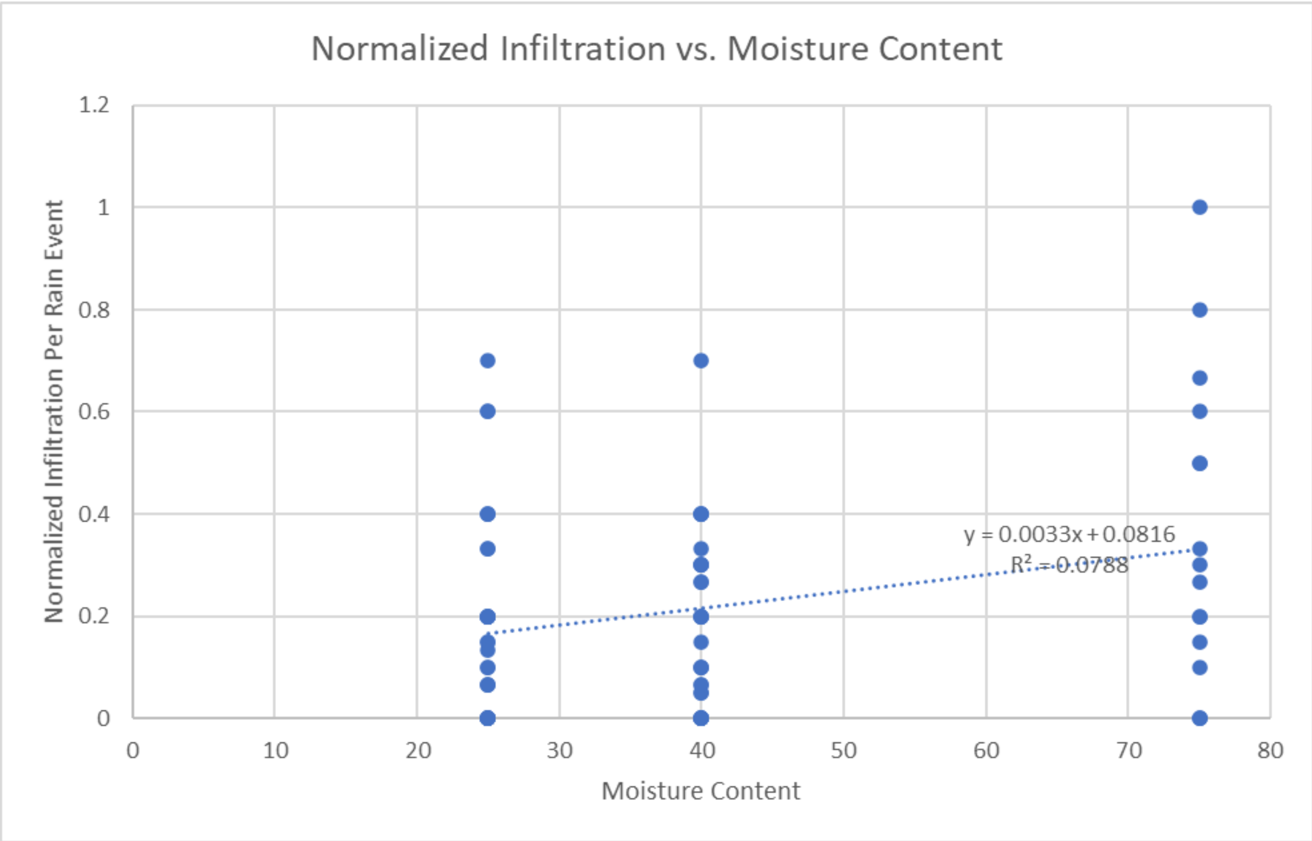

Figure A1. Normalized infiltration is shown in contrast with Moisture Content of each compost blend.

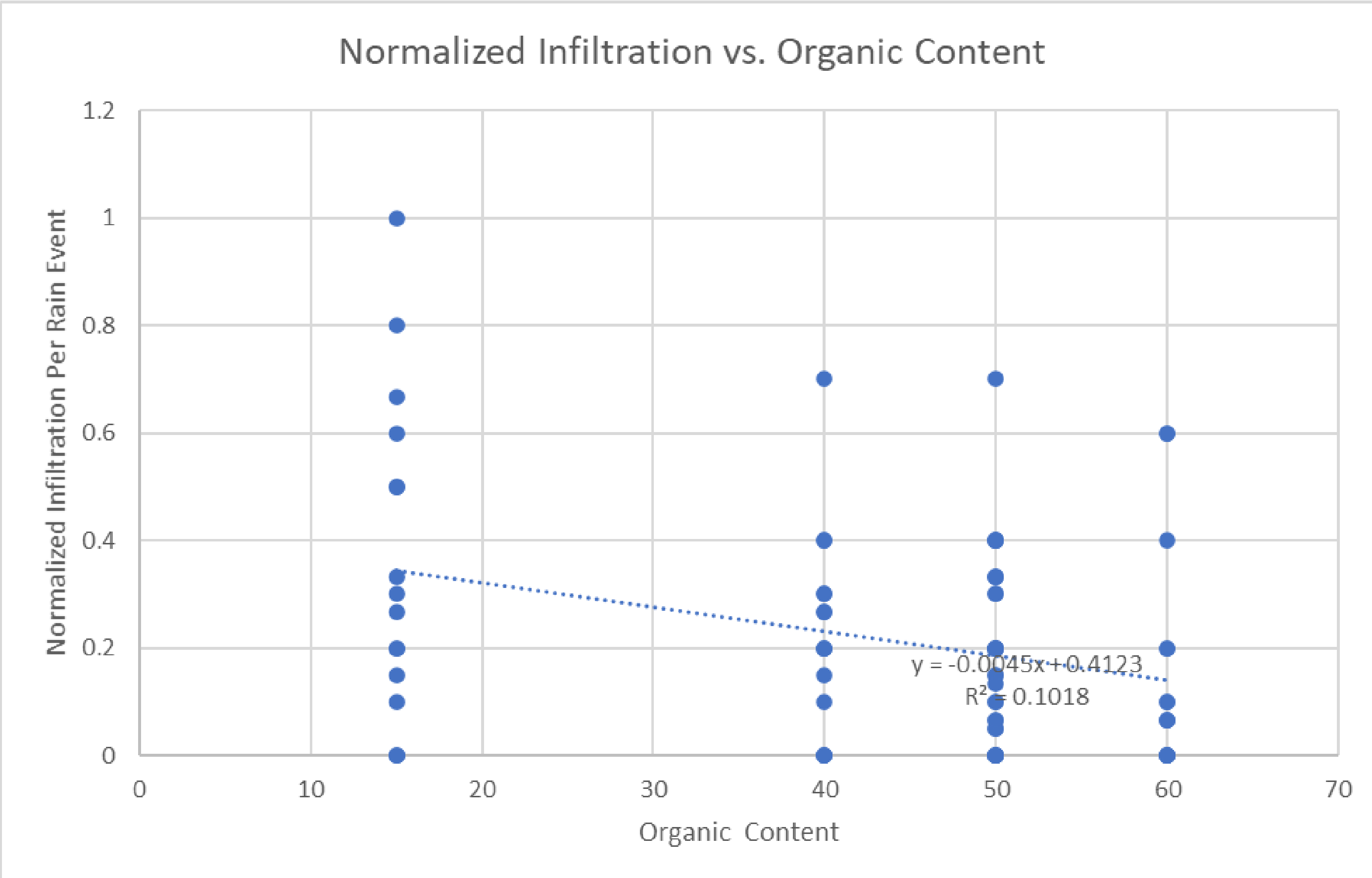

Figure A2. Normalized Infiltration is shown in contrast with Organic material content in each compost blend.

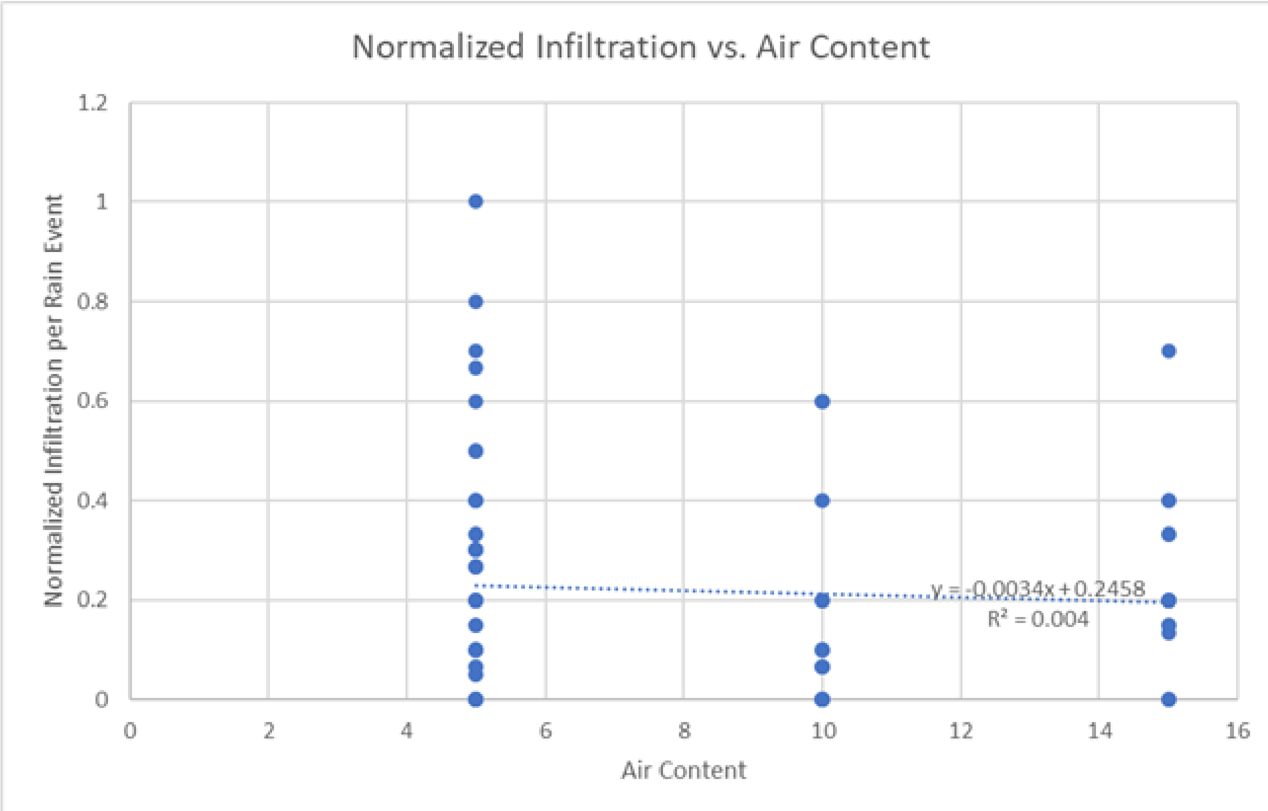

Figure A3. Normalized infiltration is shown in contrast with air content in each compost blend.