Reuse of paper mill sludge for hydroseeding and food crop applications

by

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ABSTRACT

Pulp and paper mills produce a waste, sludge, which is typically composed of waste fiber, clay, and treatment additives. This industry-focused case study explores the capacity of sludge for use hydroseeding applications and/or plant growth medium as a soil amendment. Hydroseeding testing with sludge as a replacement for the typically used cellulosic additive took place through bench-scale outdoor and greenhouse-based trials on a 3:1 incline, and a large-scale flat outdoor laydown area. Use of pulp and paper mill sludge for hydroseeding is a novel consideration, creating a value-added product from waste that is typically landfilled or burned with minimal calorific value due to a moisture value of 70%.

Study objectives included defining the capability of pulp and paper mill sludge to replace the cellulosic component used in hydroseeding applications while determining the ideal application rate on an incline plane along with consideration into the uptake of heavy metals into the plant material. Sludge with embedded seed at loadings of 5 to 25% on soil was shown to speed up germination, but after 3 weeks post application with mixtures containing 5 to 75% sludge provided the densest coverage. Transfer of heavy metals was below regulatory levels in all samples.

Greenhouse trials with lettuce (*Lactuca sativa*), carrots (*Daucus carrota*), and strawberries (*Fragaria × ananassa*) were used to evaluate sludge's nutrient availability and bioaccumulation to determine if it can also be utilized alone or in combination with Promix to promote plant growth. Lettuce flourished within the first three weeks post-transplant, increasing speedof germination, while carrot and strawberry samples did not see increased speed of germination with sludge addition. Strawberries however showed the potential to grow in up to 50% sludge while carrots and lettuce succeeded in up to 25% sludge. Bioaccumulation factors of key nutrients in lettuce and carrot samples were < 1 apart from magnesium, sodium, boron, and zinc.

Sludge has the capacity to replace the typical cellulosic additive in hydroseeding mixtures without detrimental effects and shows potential for use as a food crop soil amendment. Long-term growth trials are needed to further pursuit of this waste valorization option.

LIST OF ABBREVIATIONS AND SYMBOLS USED

ANOVA – Analysis of Variance

BCF – Bioconcentration Factor

BOD – Biological Oxygen Demand

CA – Cellulosic Additive

CCME – Canadian Council of Ministers of the Environment

CFIA – Canadian Food Inspection Agency

COD – Chemical Oxygen Demand

CT – Carrot Trial

DF – Degrees of Freedom

DW – Dry Weight

EC – Electric Conductivity

EFP – Environmental Farm Plan

FT – Field Trial

FW – Fresh Weight

ICP MS – Inductively Coupled Plasma-Mass Spectrometry

IT1 – Indoor Trial 1

IT2 – Indoor Trial 2

LT1 – Lettuce Trial 1

LT2 – Lettuce Trial 2

PM1 – Paper Machine 1 (Newsprint)

PM2 – Paper Machine 2 (Supercalendared Paper)

NSP – Nova Scotia Power

OT1 – Outdoor Trial 1

OT2 – Outdoor Trial 2

PCA – Principal Component Analysis

PHP – Port Hawkesbury Paper

S-P – Sludge – Promix (accompanied by value of sludge mass percentage)

SRF – Slow-Release Fertilizer

ST – Strawberry Trial

TMP – Thermomechanical Pulping

TDS – Total Dissolved Solids

TF – Transfer Factor

WAS – Waste Activated Sludge

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CHAPTER 1 INTRODUCTION

1.1 The Pulp and Paper Industry

The pulp and paper industry in Canada has undergone notable changes in the past decade while battling the technology era to remain a flourishing industry. While many mills have undergone closures, those who remain can be considered necessary but also immensely competitive (Oncescu, 2015, MacDonald, 2017).

Considering paper mills in Nova Scotia, Port Hawkesbury Paper (located in Port Hawkesbury) remains following Northern Pulp's (Pictou) 2020 closure (Woodbridge, 2015, Hoffman *et al*., 2015, MacDonald 2017). Both Northern Pulp and Port Hawkesbury Paper underwent a series of ownership changes during their lives. To date Northern Pulp is still in the process of working toward reopening and burning biomass to sell the energy (Baxter, 2023).

Closures of such heavy industries can be devastating to the population, especially in rural areas. In Port Hawkesbury the main industries are Nova Scotia Power and Port Hawkesbury Paper. This rural area relies heavily on the success of these industries and many residents are in some way connected to one of these industries. If a closure were to occur the unemployment rate has the potential to force residents to relocate or travel long distances to make their income (Oncescu, 2015).

"Port Hawkesbury Paper (PHP) is one of approximately 30 paper mills in Canada surviving, down from 50 operations in 2000," (MacDonald, 2017) producing super calendared paper (magazine style). PHP has a long history, first opening in 1962 under the Stora Enso title, being a new paper producing industry which flourished until the early 2000s after which a series of ownership switches took place. In 2006 a 10-month lockout occurred which caused the first mill sale to New Page in 2007/08, of which the owners took a new direction by adding in the production of super calendared paper. With a decline in the paper industry the mill again fell short and went into what looked like indefinite closure in 2011 but within the year a Vancouver Company, West Linn Paper purchased the seemingly failing mill and reopened in 2012. Since the reopening, the mill has become one of the strongest entities in the paper industry. In 2013 Paper Machine 1 (PM1) which produced newsprint was shut down indefinitely and later demolished. This decision was made due to the decrease in newspaper consumption caused by an increase in online reader popularity. To date PHP produces 4 supercalendered paper products:

- Artisan and Prominence Plus which are magazine or catalogue style,
- Prominence which is for magazines and/or inserts, and
- Maritime which is for inserts, and/or flyers.

These products are produced through the remaining Paper Machine 2 (PM2) section of the mill.

It is common to hear of paper mills shutting down as the need for physical paper products is being reduced by the ease of technology. While there will always be a need to some extent for such products, a mill can no longer rely solely upon one output. This bolsters the need for networking and creating mutually beneficial connections through an eco-industrial park arrangement.

The pulp and paper industry produces a biosolids output, namely sludge. Sludge is composed of fiber left over from the paper making process along with clay and treatment chemicals (MacDonald *et al.,* 2018). The composition of sludge has the capacity to vary based on several factors such as the industry's pulping process, the type of paper being produced, bleaching and brightening additives such as clay, and the secondary treatment process. Pulp and paper mill sludge valorization is not a new research avenue, but management of this resource varies across the industry. Anaerobic digestion has been used for valorization, along with biomass burning, land application where regulations permit, and other options, but landfilling appears to be the most common method of disposal (Zibilske, 2000, Faubert *et al*., 2016, Faubert *et al*., 2019, Srivastava, & Chakma, 2021). Economics are often the limiting factor in reuse beyond landfilling. However, as indicated by Faubert *et al*., (2016), in some regions this is not an option as landfilling is highly regulated or banned to promote more sustainable practices.

As Faubert *et al*., has pointed out through cumulative research review, the application of pulp and paper mill sludge had potential in land application, whether it be through increased yield, nutrient increase, or increased germination. Room exists however to consider hydroseeding specific applications, using paper mill sludge with embedded seed through spraying.

1.2 Literature gap for study

While literature reviews the use of paper mill sludge or biomass for the growth of plants in general, the specific use for grass or hydroseeding purposes is lacking. Literature to date would indicate minimal benefits and, in many cases, negligible value of using paper mill sludge for plant growth compared to typical fertilizer-based applications. Comparably, hydroseeding, or growth of grass in general has a higher chance of success due to the ruggedness of grass, being able to grow in harsh conditions and with minimal nutrients. Additionally, while consumables have been tested with varied pulp and paper mill sludge streams (de-inked, primary, and secondary), the specific considerations of lettuce and carrots are unique. In this study these consumables are utilized to address the benefits and/or detriments if any exist in growth using Port Hawkesbury Paper’s sludge which follows a thermomechanical pulping (TMP) process with kaolin clay and is combined with the industry’s sanitary sewer line. Various methodologies for pulping exist, with TMP being a newer, highly energy intensive operation. This work would also address the concern of leaving the sanitary sewer line connected to the process sewer. More specifically, does the presence of fecal coliforms exceed the regulations for ground application and would the bacteria transfer into the consumables or grass if used for land application?

The proposed work considers Figure 1 as the general outcome process, as proposed to the case study industry. Paper is produced as the fundamental product of the pulp and paper industry with sludge being ejected as a waste. This waste will then be combined with grass seed, soil, and water to create a hydroseeding slurry which is then sprayed on a laydown area such as the side of a newly developed highway. This will then allow for the growth of grass and remove the need for sludge to be placed in a landfill or burned for minimal energy gain.

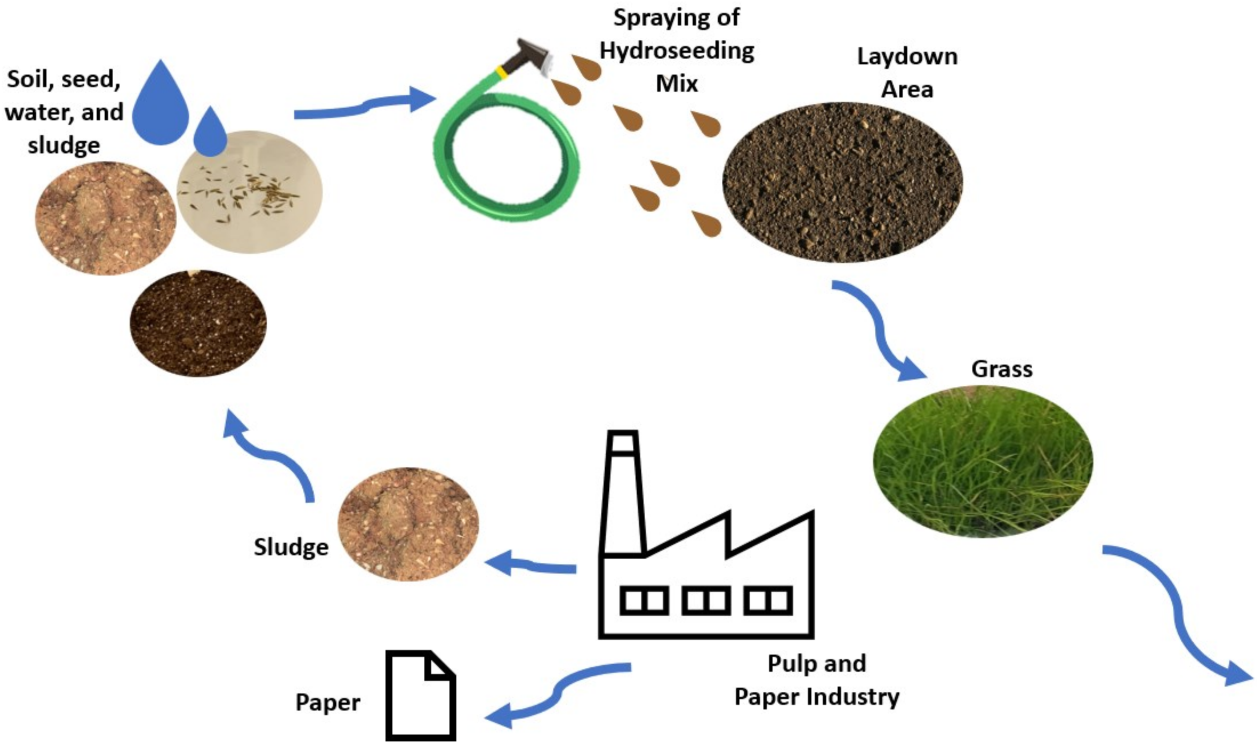

Figure 1 - General flow of materials utilized in sludge, from industry waste to final grass product.

Considering again that this is regionally focused work, PHP has limitations to end use potential, due to space, economics, location, current disposal and/or storage options, etc.

1.3 Research Questions/ Study Significance/ Objectives

While studies have occurred regarding the use of sludge as a soil amendment, a gap exists in the determination of the usefulness of pulp and paper mill sludge in the capacity of a tacking agent for use in hydroseeding. Research considering land application of sludge is diverse in the production methods which are specific to each pulp and paper mill. For example, this could relate to kraft pulp, TMP, deinked newsprint, etc. Work has been conducted to evaluate sludge's use in agriculture, silviculture, land reclamation, growth of turf grass, and composting (Faubert *et al*., 2016). Port Hawkesbury Paper's sludge is a regionally unique process, using thermomechanical pulping and kaolin (high quality and brightness) clay.

Published research on pulp and paper sludge use for hydroseeding in general is sparse and it is possible to further expand this knowledge base and identify paper mill sludge as a better option for hydroseeding than the conventional paper-based cellulose mixture. Turf grass growth facilitated through the use of primary and deinked sludges was studied and consideration was given to rate of germination, ground cover, and stand quality (Norrie & Gosselin, 1996, Dexin *et al*., 2012). Hypothetically, paper mill sludge has the capacity to not only replace the cellulosic component typically used in hydroseeding applications, being shredded newspaper.

Again, a gap presents itself regarding pulp and paper mill sludge in hydroseeding specifically replacing the typically used cellulose additive. The sludge not only provides the cellulosic portion required for the application but provides additional benefits such as nutrient availability.

The overall objective of this research study was to investigate the potential to use pulp and paper mill sludge in hydroseeding to replace the cellulosic additive commonly used through direct consideration of grass growth and soil amendment applications on various plant subjects.

The specific objectives of this project were:

1. To determine the optimal application rate of sludge with embedded seed to replace the typically used cellulosic additive in hydroseeding.

2. To Investigate the potential for sludge to be used as a soil amendment with Promix in the growth of lettuce (*Lactuca sativa*), carrots (*Daucus carrota*), and strawberries (*Fragaria × ananassa*).

3. To evaluate the bioaccumulation and transfer factors of hazardous analytes such as heavy metals within all mixtures and plant products.

1.3.1 Research Questions

1) Does paper mill sludge have the potential to be used as a soil amendment?
2) Is paper mill sludge a better additive for hydroseeding purposes than the typical cellulosic component?
    a. Is growth period reduced with sludge?
    b. What is the ideal application rate and composition of a sludge-hydroseed mixture?
3) Does paper mill sludge have the capacity to replace the need for a tacking agent in hydroseed applications.
4) What pre-treatments are needed to create a 'usable' mixture for land application, if any?

1.4 Introduction to the Following Chapters

Chapter 2 considers relevant literature, specifically investigating the pulp and paper industry within Canada, eco-industrial parks, and a review of the research project goals. The purpose of this chapter is to provide a storyline leading to the pursuit of plant growth and hydroseeding utilizing pulp and paper mill sludge. The journey taken to this point has involved numerous evaluations of sludge valorization. The chapter aims to highlight pros and cons to eco-industrial parks, and the choices made when considering becoming a partner and/or anchor tenant. This directly relates to the focus industry, PHP, as they actively pursue sustainably minded industrial operations in the form of symbiotic partnerships. Additionally, the hydroseeding process is explored along with limitations to utilizing sludge in a land-based capacity.

Chapter 3 discusses overall methodologies utilized. These methodologies are re-described in individual chapters where the chapters are written in article form.

Chapter 4 focuses on hydroseeding specifically, investigating a series of indoor and outdoor small-scale trials, compared to a large-scale outdoor trial conducted by a hydroseeding company.

Chapter 5 undertakes a greenhouse-based growth trials of 3 plants, a leafy green, root vegetable, and fruit with the goal of considering paper mill sludge as a general additive for plant growth. Within this chapter, both qualitative and quantitative considerations are provided. Recognizing the potential for heavy metals to be present in PHP's sludge, heavy metal uptake and nutrient value have been investigated in product plants.

Chapter 6 contains conclusions drawn from the study along with the potential for future work on this study topic.

Appendix A provides information on an early project proposal for the consideration of PHP's sludge for use in commercial sale through comparing to it wood pellets for burning.

Appendix B provides supplementary information on the land trials for hydroseeding. This work acts as a supplement to the information provided in Chapter 4 through publication.

Appendix C provides supplementary information on the bench-scale growth trials for hydroseeding. This work acts as a supplement to the information provided in Chapter 4 through publication.

Appendix D provides supplementary information on soil characteristics of mixtures of soil and sludge used in growth trials throughout this work. This appendix specifically provides further information on the methodology for collection of characteristics such as pH and conductivity. The results of this work are seen in Chapter 5.

Appendix E provides supplementary information on the carrot growth trials. This work acts as a supplement to the information provided in Chapter 5 through publication.

Appendix F provides supplementary information on the lettuce growth trials. This work acts as a supplement to the information provided in Chapter 5 through publication.

Appendix G provides supplementary information on the strawberry growth trials. This work acts as a supplement to the information provided in Chapter 5 through publication.

Appendix H provides full metals analysis for PHP’s sludge over 3 points of collection, 2 in 2018, and one in 2022. The aim of this information is to identify seasonally affected characteristics

Appendix I contains a series of water tests undertaken on PHP’s output streams considering the presence of heavy metals and contaminants. These tests were utilized to supplement data in Chapter 5.

Appendix J discusses business considerations which are made with the results from the preceding chapters in mind.

CHAPTER 2 LITERATURE REVIEW

2.1 Eco-Industrial Park Review

Eco-industrial parks operate on the premise of conversion or transfer of one industry's waste into another industry or process's feed stream creating a symbiotic relationship rather than a more old-fashioned cradle to grave approach. While a product-focused approach is profitable, it has adverse effects on the ecosystem and is rooted in outdated mindsets (Veleva *et al*., 2015). Instead, considering the industry setting as part of an ecosystem that must adapt to the ever-changing environment promotes success and fosters the cradle-to-cradle approach (Lowitt & Côté, 2013).

As regulations become stricter and the global focus shifts to reducing carbon footprints, productivity alone can no longer remain paramount in industry. This changing atmosphere has caused many industries to not only re-evaluate their current processes, but in some cases has caused a search for collaborative partners. Reduction in carbon footprint is often found through technology changes and methods of energy reduction, however this is often challenging in developed heavy industrial settings. A symbiotic approach can often accomplish the same goal without the need for large scale equipment changes. Additionally, symbiotic relationships are beneficial to multiple parties by removing or reducing waste production, creating feed streams, creating jobs, and allowing industries to develop long-term sustainable partnerships (Owttrim *et al.,* 2022).

With over 220 EIPs currently document, there is an important differentiation to be made between the various types of industrial parks. Côté (2010) described industrial parks as having 6 options. The first being the standard industrial park, which is largely just a group of businesses or industries in a common area. There are not necessarily connections between any of the tenants. An eco-labeled park is similar to an industrial park but with an active focus on environmental practices. Environmental industrial parks are a system of businesses that produce environmental products. Eco-efficient parks focus on mindful use of resources. Environmentally balanced industrial clusters are cognizant of partnerships and take part in co-locating where possible. Finally eco-industrial parks are focused on co-location, methods of reducing waste, regularly change due to best practices. Not all EIPs are completed or fully documented apart from their existence and main goals of which all similar operations share similar objectives.

2.1.1 What Constitutes a Good Eco-Industrial Park?

Studies have taken place to identify desirable qualities for eco-industrial parks, with the greatest draw being access to transportation infrastructure. Presentation of opportunities has been identified as a concern and potential roadblock to forming effective, sustainable partnerships. Moreso, dedication must be given to networking (Veleva *et al.,* 2015). Veleva *et al.* (2015) have indicated that eco-industrial parks need not focus on the sharing of physical materials but can prosper through the sharing of knowledge and infrastructure. This has been key in PHP's work to date, with interest from various stakeholders bringing to light potential connections and showing interest in working with the industry.

Options must be pre-developed to find the optimal location for transport services as one may assume that an industry will be moving and/or receiving products. Once this is established gathering participants is the next step and often multiple linkages can be established with a large initial industry (anchor tenant). In the case of smaller businesses, multiple may join an industrial park before any connections can be made, as is a similar case to the Burnside EIP to be discussed.

Research and development must go into creating and perfecting an EIP and typically large investments are made. Such investments should not be made with haste as the timeline for payback is crucial, as if compensation is not foreseen the project is not completely eco-industrial (Lowitt & Côté, 2013) as there must be a balance between industrial profitability and environmental sustainability. An EIP ideally would not yield any waste which cannot without consequence be emitted into the environment, but in many cases, this is currently not possible. The optimal interconnected system can only be sought out by strong communicators and forward-thinkers.

2.1.2 Established Networks External to Canada

Numerous eco-industrial parks exist outside of Canada and have been studied extensively. Zhu & Ruth (2014) culminated a list of EIPs considering self-organization-based, coordinated, planned, and utility EIPs, which was then further divided into firms, pairs and clusters. In these EIPs it is not necessary that all members or tenants work together. In most cases smaller groups are formed and it is seen that multiple clusters are rarely formed. The following work will highlight several of the more well-known EIP examples.

2.1.2.1 Kalundborg

Kalundborg, Denmark houses what is perhaps the most well-known example of an EIP with numerous publicly and privately-owned operations (Symbiosis.dk, 2016) working in sync to limit negative environmental effect. This park has been an ongoing project since the 60s, not initially sculpted on the grounds of symbiosis, but purely on a nearby partnership basis to avoid outsourcing. Kalundborg is still based on helping nearby industries but has a clearer focus on overall decrease in waste since 1989 when the network was first identified as an example of ‘industrial symbiosis’ (Symbiosis.dk, 2016). The Kalundborg EIP continues to evolve and is an unfinished project with more opportunities to be developed to protect the longevity of the industries and the EIP. This is especially the case where one waste stream can be re-used by multiple partners (Chopra & Khanna, 2014). Esso, most recently renamed the Kalundborg Refinery was the foundation of this symbiosis, starting off in 1961 and at the time required a water source leading to a linkage between the refinery and the nearby lake, Lake Tissø. The refinery later partnered with Haldor Topsøe Ltd., taking the sulfur and nitrogen rich waste product from crude desulfurization and converting it into a fertilizer by forming ammonia thiosulfates. Synflex then joined as partner sulfur-free diesel oil. Gyproc formed an alliance with Statoil by consuming the refineries' natural gas product to power the ovens used in the drying of plasterboard. Dong Energy is a producer of electricity and district heating. They supply steam to the refinery and Novo Nordisk and Novozymes, producers of pharmaceuticals and enzymes. They also were looking into partnering with Inbicon to use straw for fuel formation from which ethanol could be produced and replace coal as the fuel at the power plant, which results in greener power generation. There is also a wastewater treatment system in the area and from this as well as other industries waste is produced which can be used for soil and on farms.

Esso was the foundation of this symbiosis, starting off in 1961. This industry is now known as the Statoil refinery and at the time required a water source leading to a linkage between the refinery and the nearby lake, Lake Tissø. Statoil is a producer of gasoline, propane, heating and fuel oil from light oils and crudes. Apart from gas and oil production, the refinery later partnered with Haldor Topsøe Ltd., taking the sulfur and nitrogen rich waste product from crude desulfurization and converting it into a fertilizer by forming ammonia thiosulfates. Apart from creating another industrial opportunity, sulfur and nitrogen emissions have seen an increase following collaboration. Synflex then joined as partner sulfur-free diesel oil (Statoil.com, 2016). Gyproc formed an alliance with Statoil by consuming the refineries' natural gas product to power the ovens used in the drying of plasterboard. Dong Energy is a producer of electricity and district heating. In the Kalundborg location the industry links to the same water line Statoil uses and is working towards a biofuel initiative with producer Inbicon to use straw in forming fuel. This plant is also a steam supplier to Statoil, Novo Nordisk, and Novozymes (Novonordisk.dk, 2016). This steam also goes to breaking down the straw for biofuel and in turn "the residual biofuel from the ethanol plant is used by the power station to replace coal as the fuel, which results in greener power generation. The Inbicon cellulosic ethanol process consumes less energy than it produces in the conversion of biomass. This results in energy efficiency and cost reduction of both plants (Chemicals Technology, 2016). Novo Nordisk produces pharmaceuticals, taking in surface water and wastewater is sent to Novozymes, an enzyme producer. Heat is also made by Kara/ Novoren through the use of wastepaper.

Dong Energy announced the initiative that by 2018 the Asnæs Power Station will utilize woodchips rather than coal for the production of steam, heat, and electricity – moving towards a more sustainable process. (Dong Energy, 2016)

These industries have more commonly shared residuals than is described above, but this grouping holds the largest insulin and enzyme producers in the world. 5 main'cliques' have been identified:

"1: Novo Nordisk Novozymes Asnaes Power station Statoil refinery2: Asnaes Power station Statoil refinery Gyproc

3: Asnaes Power station Statoil refinery Component recyclers

4: Novo Nordisk Novozymes Asnaes Power station Municipality

5: Novo Nordisk Novozymes Farmers (Domenech & Davies, 2011)"

Kalundborg continues to grow as new opportunities become available (Kalundborg Symbiose, 2019).

2.1.2.2 Kwinana

This Australian EIP is in an area rich in nickel, iron and other valuable exports. It is a largely heavily industrialized sector. Industries vary from chemicals and power plants to a worm farm. The location of this network is also near a deep waterway which is used for transport between Asia and Australia. Industries contained here are the Alcoa alumina and nickel refineries, Alcoa, Tiwest, a producer of titanium dioxide pigment, an oil refinery, herbicide producers, water treatment plants,and coal and gas power generation plants. The relationships seen here are many, and one standout portion of this is the composting facility, which seems to lack a contribution to another industry. The contribution in this account is to the environment, showing that industries do not need to only feed each other to form a sustainable network.

2.1.2.3 Ulsan

This park in South Korea is part of a large mass of EIPs with teams governed by 'champions' who are government chosen representatives guiding creation of EIPs and this champion is part of KICOX, a larger evaluating party. Steam is one of the key players in this highly industrialized network as it is supplied from the incineration of industrial waste of other operations such as a paper mill. An unlikely example of a partnership by company description would be zinc smelting and paper production, but the steam comes from this plant as well as the incineration plant along with carbon dioxide and can be readily used in the paper making process for the creation of calcium carbonate. This EIP sees air pollution reduction and cost savings as an investment with the longest payback period being slightly more than 3 years, but most in under a year (Behera *et al.,* 2012).

2.1.2.4 Gladstone

Gladstone is located in Queensland, Australia with its largest industries including a coal powered plant, alumina refineries and smelter, and an ammonium nitrate producing plant. This is made up of 1 small synergistic network (Corder *et al*., 2014). Domestic tires are used in these plants along with waste fuel, spent cell linings from the alumina refinery. Many waste materials are recycled (~85% in this case) or stored awaiting reuse or reselling, which may not be optimal for a sustainable sector, but this is a better option than landfilling. (Beers *et al*., 2008).

2.1.3 Eco-Industrial Potential in Canada

To follow are a few examples of nationwide industrial parks with the clear potential to form an eco-industrial network but are in the early stages of establishment, being initial communication with potential cluster or nodal partners, although, nodal (similar feed points) formation ideas may be formed but have yet to be documented.

Red Deer Alberta is working on beginning an eco-industrial sector and is currently inviting interested industries to move into the site. The site goals will be to preserve natural habitat life, reduce the carbon footprint of all involved partners, and many other draws to potential industries looking to improve upon their sustainability. The development information for this park also notes some small changes that will be implemented to make a large difference such as idle-free zones and irrigation systems (Reddeer.ca, 2016). In the Halifax Regional Municipality ice-free waters are accessible for transport purposes. Port of Sheet Harbour area industrial park also houses many businesses relating to fishing, forestry, electricity generation, construction, finance, food services, etc. (Sheet Harbour Nova Scotia Business Case, 2016). The Woodside Industrial Wharf is located in Dartmouth, Nova Scotia and is close to an airport, and the busy downtown area, separated by an easily crossed harbor with an area ideal for oil rigs. This wharf boasts ice-free ports also has onshore electrical and water supplies making this ideal for domestic and commercial operations (Novascotiabusiness.com, 2016). The Burnside industrial park falls under both the established and potential category. This park is unique in the fact that not only does it house small to mid-size businesses (over 1,500), but it is also the subject of much research by Dalhousie's School for Resource and Environmental Studies which also runs an Eco-Efficiency Centre. Around 15% of the industrial members in this park provide recycling or re-use options. Transport, sales (heating, ventilation, cooling, electronics, chemicals, etc.), transit, hotels, and various other businesses make up this large park, not all of which are participating in the EIP initiative at this time. Many options are available such as production of liner board from reused corrugated cardboard, furniture repurposing, paint exchange, and silver recovery (Newcity.ca, 1996). Housing over 400 businesses, the Ross park is located atop an aquifer Regina, Saskatchewan (Chandra, n.d.). The location may not be ideal in this case as storm water issues have arisen, but highway proximity is great in this case.

2.1.3.1 Point Tupper/Bearhead Industrial Park (Cape Breton, Nova Scotia)

Cape Breton, Nova Scotia has made an effort to initiate investigation into an industrial park which could turn eco-industrial located in the Point Tupper/ Bearhead area. The idea of a Point Tupper industrial park is not new, but instead is resurfacing with enthusiasm. PHP announced in January 2023 the submission of a proposal for a 29-wind turbine wind farm, expanding beyond the typical papermaking process, which would facilitate up to 40% of the typical electricity requirement of PHP (Willick, 2023). PHP is also looking at partnering with Charbone Green Hydrogen to implement a small-scale demonstration facility which in the future, depending on success, could lead to project growth (Boudrot, 2022). Within this article, Geoffrey Clarke, Director of Sustainability and Economic Development, boasts the value of partnering with PHP stating due to the land and amenity availability. At this time PHP utilized approximately 10% of the province's overall energy output to support the industry's activities (Lowthers, 2020). This park has yet to become fully established but boasts many positive qualities such as access to waterways for shipping in an ice and dredge-free harbor along with other modes of transport through highway, rail, etc. This area is available and home to commercial, light, and heavy industries (Novascotiabusiness.com, 2016). There is currently a small part of what could easily become a symbiotic system; Port Hawkesbury Paper LP and Nova Scotia Power Point Tupper are neighboring industries and have a currently established biomass burning agreement. A portion of the waste sludge from the paper mill is directly transported into the power plants biomass burner. A portion of this waste sludge is currently going to landfill, but this sludge could become a necessary intake product for many operations or for possible reuse within the plant.

An engineering consultant undertook an initial study identifying quality of waste streams at PHP in 2015 (MacAskill). This study sparked interest in continued efforts toward reuse of numerous streams at PHP, not limited to the sludge product, which is the focus of this work.

2.2 Information on Case Study Industry – Port Hawkesbury Paper:

Port Hawkesbury Paper has historically undergone numerous ownership changes, originally being Stora Enso beginning in 1960, a Finnish company, which was a producer of newsprint. This changed following a lockout in 2006 where the company then sold to New Page in the following year. New Page added magazine style paper to the mill’s products. In 2011 New Page closed indefinitely, however, a Vancouver company purchased the mill and reopened in 2012. One year later PM1, the newsprint machine was shutdown indefinitely. PHP remains a competitive producer of supercalendered paper.

2.2.1 Paper making process – Port Hawkesbury Paper

Supercalendared paper at Port Hawkesbury Paper is produced through the operation of a thermomechanical (TMP) pulp mill, a kaolin clay plant and 400,000 short tons per year (Figure 2).

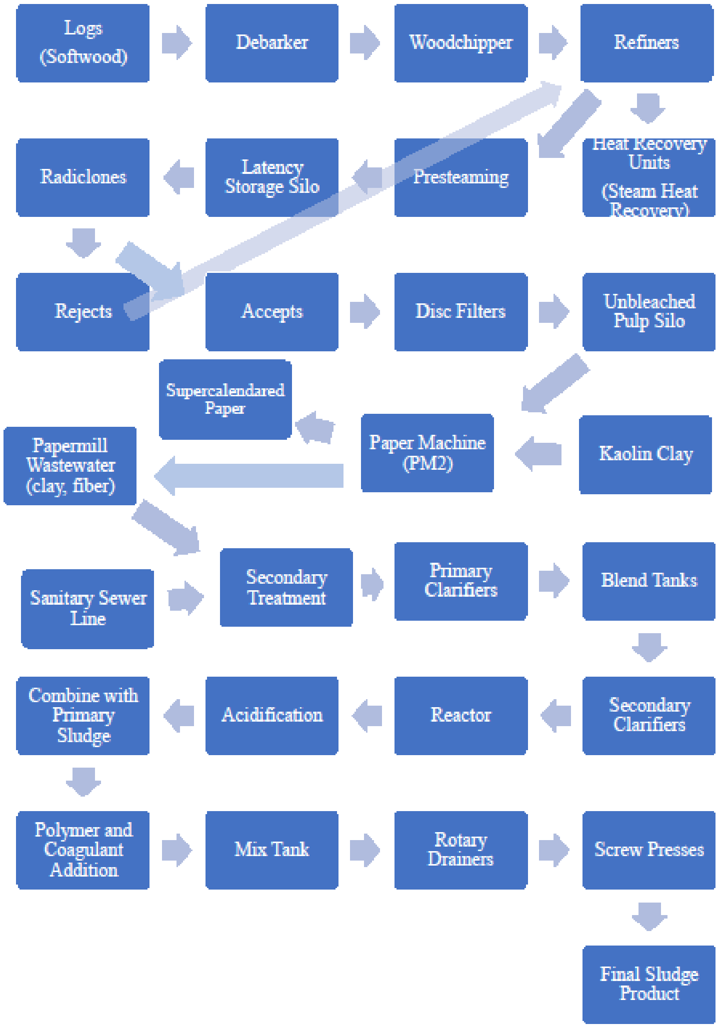

Figure 2 - Process Overview of Port Hawkesbury Paper

Softwood logs are input onto a log feed deck which allows for the transport of the logs into the debarker or fuji, entering the woodroom where the logs collide with one another to facilitate the removal of bark. Once debarked, wood chips are created through a woodchipper and sent along to a storage silo and then further to presteaming which utilizes 30 lb steam where the chips remain for approximately 25 minutes. The next stages are a series of refiners to allow for the separation of the chips into individual fibers. Heat from the refiners is recaptured through heat recovery units with the product being steam. Refined product moves along to a latency storage silo which is required to take the now curled fibers and allow them to settle out to then move through the screens and pumped onwards to the radiclones which are hydrocyclones utilized in the removal or dirt and unwanted particles. One may note that the rejects are extracted; rejects being chips of undesirable size are separated and further refined.

The accepts continue to the disc filters facilitating dewatering through screens and the product moves forward to yet another storage silo, the unbleached pulp silo. The product from this silo is introduced to the twin wire presses where continuous dewatering occurs between two synthetic membrane belts and takes part in the continued bleaching process in the bleach plant and then moves on to be stored in the bleached pulp silo.

This pulp moves then onto the paper machine itself; the process moves through the supercalendars which are a felt roll and hard roll with 450lb steam injected to give the shine followed by the winders. The two main products are created – paper and wastewater. The paper moves on to a wrap line and then onwards to the warehouse for shipment.

The wastewater is sent to a secondary wastewater treatment facility. The wastewater first enters the primary clarifiers where the bottoms (or thicker sludge) is sent directly to a blend tank in the dewatering building, but the overflow and acid sewer head to the inlet pumping station. This combination then moves along to the secondary clarifier where overflow leaves to the reactors and bottoms leaves to WAS pumping building. At this point the WAS is injected with acid to foster dewatering and then once at the dewatering building and meeting up with the primary sludge in a blend tank, additional chemicals, polymer and coagulant are introduced and the overall mix is then moved to the top floor of the building into a mix tank. From the mix tank the sludge enters rotary drainers followed by sludge presses, from here the sludge leaves two one of two final destinations, Nova Scotia Power's biomass burner, or to an on-site landfill.

PHP's secondary treatment process is represented as including a series of clarifiers, primary and secondary sludge, the addition of dewatering chemicals (polymer, coagulant, and sulfuric acid) and movement into a blending tank. This process can be followed by a series of dewatering steps and the addition of sawdust. Additionally, clean water and treated effluent from the secondary clarifiers can be removed safely from the mill site, adhering to testing requirements.

2.3 Re-Utilizing Bio-Solids/ Sludge and Considerations to Date

PHP, while flourishing as a paper producer, also produces large amounts of waste sludge. This sludge is composed of bugs, pulp, ash, sawdust, and a small amount of sanitary sewage, etc. More than 7 tonnes/ hour is made with a large percentage typically being used to augment NSP's biomass burners in their Point Tupper location, but while this takes care of most of the waste, the unburned product is taken away by truck or is placed in an on-site landfill. Landfilling can be avoided if more sludge was either burned or if another use could be found. The final sludge product varies in dryness from 25-38% depending upon the seasonal conditions; in the colder months a film is formed due to the bacteria *Microthrix Parvicella* on the secondary clarifiers creating difficulty for moisture release and will likely increase the amount of polymer needed in the dewatering process (Environmental Leverage, 2003).

This work focuses on linkages between PHP and outside potential partners to benefit the local economy and beyond. With PHP's goals in mind, the greatest focus is waste cellulose sludge reuse. In the past various concerns have been noted with regards to public use, such as odor and small presence of fecal coliforms. While domestic waste may seem like an inhibitor, through research it has been proven to contain a lesser concentration of heavy metals which are undesirable for land application (Sawhney & Norvell, 1980). As previously mentioned, the sludge could be used as a soil amendment due to its fibrous make-up which will aid in water absorption and retention.

In a broader sense, the idea of waste reuse in the pulp and paper industry has been investigated; however, each paper mill has specific characteristics (such as pulping process, chemical use, etc.) validating the need for a case study investigation. On average, "in the United States, approximately 4.1 million dry tons of sludge are produced each year" (Scott *et al*.,, 1995). Scott *et al*., (1995) went on to describe the typical sludge breakdown, being primary sludge (easily dewatered) and secondary sludge (dewatering is more difficult due to the presence of adapted bacteria, formation of filaments, etc.). That study also expanded further into all waste products, and similarly to PHP (and many other paper producing entities), sawdust and bark are products; this report even delves into mechanical faults such as loss of product from overfilling or screening. Interestingly, Scott *et al*., (1995) incorporate Stora Enso, a previous company located on what is now PHP's land. Waste statistics from this report indicated that solid waste production is greatest in tissue and market pulp grade paper, followed by supercalendered paper, newsprint, and packaging paper.

PHP has the potential to consider utilizing their waste sludge which is comprised largely of isolated softwood fibers to form wood pellets for commercial burning by local power generating stations in their biomass burner if the solids content of the mill's sludge can be increased sufficiently.

There is also the potential for use as a soil amendment; "secondary sludges can also be applied to land as a soil improving organic fertilizer, if the material does not contain chlorinated organic compounds (or adsorbable organo-halogens), as most of these are acutely toxic to fauna and flora (Walden & Howard 1981; Saunamaki 1988; Bajpai *et al.* 1999). Chlorinated organic substances are present in the solid and liquid effluent of pulp and paper mills that use elemental chlorine or chlorine dioxide for bleaching of pulp (Bajpai *et al*. 1999; Gullichsen 1991)" (Bajpai, 2015). PHP utilizes a peroxide, caustic soda and a chelating agent to conduct their bleaching process (Macdonald, 2014).

Specific to PHP, an additional study was completed in 2015 by consultant Robert Anderson of Robert Anderson Consulting Ltd. This study begins by identifying a barrier component, the minute presence of sanitary/ domestic wastewater. This has and continues to be an ongoing question at PHP with regards to the potential for commercial use of any sludge-based product from their wastewater treatment facility. While the amount of domestic wastewater in comparison to the overall paper process streams in the mix is often considered negligible, if looking at use as a fertilizer the fecal coliform count well exceeds the standards set forth in the Canadian Food Inspection Agency (CFIA) standards regarding fertilizers and supplements and also in the Canadian Council of Ministers of the Environment (CCME) guidelines (Canadian Council of Ministers of the Environment, 2005) for compost quality as seen in Table 1. This table shows that currently the PHP untreated sludge does not meet usable criteria with regards to fecal coliforms, but metals are well under the required levels for use.

Table 1 - Pathogen Reduction Requirements (Extracted from Anderson, 2015, p. 2)

Class A (Unrestricted Use)	**Class B** (Restricted Use
Fecal Coliform: <1000 MPN*/g total solids (dry weight) AND[1]/OR[2] Salmonella: <3 MPN*/4g total solids (dry weight)	Fecal Coliform: <2,000,000 MPN* per gram of total solids (dry weight)

*MPN (most probable number)
[1]CCME Guidelines for Compost Quality
[2]Guideleines for the Land Application and Storage of Municipal Residuals in Nova Scotia

Relating to Table 1, the analyzed sludge at this time ranged in coliform count between 50,000 and 1.4x 10^7 CFU/g, again exceeding the allowances. Since this testing PHP has begun injecting 93% sulfuric acid into their sludge which may reduce the presence of fecal coliforms and/or *E. coli* within the sludge. Also, unsureness exists regarding the pathogenic potential of various strains of *E.coli* as strains exist which may not be considered a danger for use, also some bacteria can present false positives in testing (Anderson, 2015). If this presents a problem, potential exists for treatment through implementation of a wastewater treatment plant which will treat separately the domestic sewer.

Anderson (2015) suggested the following as potential uses for PHP's sludge:

- Soil Amendment
- Alternative Animal Bedding
- Anaerobic Digestion
- Stabilization through blending
    - Pelletizing
    - Alkaline Stabilization
- Ag-Bag
- Drying Beds
- Concrete

Focusing further on land application of sludge, a set of regulatory guidelines to ensure safety for those in contact with the substance are considered. These guidelines vary dependent upon the intended end use of the material, be it for food growth, gardening, hydroseeding, etc. This is especially important if a product is intended for sale. Contaminants in paper mill sludges present a clear barrier to the production of salable products. For example, if using municipal wastewater solids, the Canadian Food Inspection Agency (CFIA) guidelines (Government of Canada, C. F. I. A., 2021) prohibit an excess of metals or the presence of bacteria (often as a result of human fecal matter, namely sanitary sewage). For agricultural use this is especially concerning as consumption of products in contact with such biosolid is often expected. In the case of producing a soil amendment or fertilizer with such contaminants, it could lead to surface runoff, which affects wildlife, but also human consumers if the product is utilized on farmlands.

In the specific case of the paper mill, the most obvious mitigation would be to simply divert any sanitary wastewater to a bed or treatment facility or to utilize a sterilizer such as the fly ash option. While both options are feasible would only be considered if the economic utility of the resulting sludge was improved.

The presence of metals also creates a potential roadblock; data obtained from PHP showed, based upon CFIA standards, that the waste bio-solids product satisfies regulations for all but the metals molybdenum, nickel, cadmium, and arsenic; all are within 50% of the goal value. With the appropriate changes to treatment, through replacement of current synthetic flocculants and chemicals, implementation of metals removal may be plausible.

If the end use for waste products is agriculture, specifically, for fertilizer or soil amendment use, one must ask, would the product be utilized in areas which boast the potential for fruits and vegetables to be consumed (as previously mentioned) or would the product be used for aesthetic purposes on golf courses or for general lawn care? Regulations have been growing strict in areas of lawn care, especially residential, which greatly affects a large consumer market. For example, pesticide rules have changed immensely within the last decade. “While both your lawn and garden need fertilizer to give the soil nutrients so that it can stay as healthy as possible, they both need different elements in different quantities, and even at different times” ("Garden vs Lawn Fertilizer - Is There a Difference?", 2014). Potassium is great for lawns and gardens, as well as nitrogen; however, too much nitrogen in a garden can actually cause slowing of growth; with this in mind, bio-solids mixtures would need to cater to specific fertilizer needs. Following Nova Scotia’s Environmental Farm Plan (EFP), bio-solids application must occur within predetermined distances from waterways. Fly ash, as previously discussed, has potential for use as a fertilizer or soil amendment, again, the Nova Scotia EFP states “Pulp and Paper waste is recycled to become a soil amendment. The fly ash waste from wood biomass combustion has been approved by the Canadian Food Inspection Agency as a fertilizer and lime resource for farmers’ fields. Nutrients that were once locked up in the forest biomass are now turned into a soil-liming and fertilizing ash” ("Nova Scotia Federation of Agriculture", 2018).

Coal based fly ash has also been separately approved for pre-determined land-based uses by the CFIA. Ideally, bio-solids based products would meet Class A definition by Nova Scotia government regulations (regulations likely differ extending beyond the province). Such regulations for land application (based upon municipal bio-solids – more storage and/or capping focused) could be comparative for agricultural use (Guidelines for Land Application and Storage of Municipal Biosolids in Nova Scotia, 2010).

Faubert *et al.,* (2016) has culminated information regarding research work reported relating to valorization of pulp and paper mill sludge. Their work broadly considers agriculture, silviculture, land reclamation, and composting. Pulp and paper mill sludge types considered deinked, primary, and secondary sludge. The testing parameters also varied widely, considering several plants, runoff quality, methodologies for compositing (and various composting participants such as worms). This culmination even considered mixing the industry sludge product with municipal waste streams. The most notable findings include an increase in organic material in soil when sludge is used but not detrimental to growth qualities. Soil pH was increased in many cases, and yields were increased in grain products (as high as a 34% increase with corn (Gagnon & Ziabi., 2012). The de-inking process appeared to have a positive effect on the products as well, increasing availability of analytes such as zinc.

Paper mill sludge and grass growth has been considered by Norrie & Gosselin (1996), specifically comparing deinked paper mill sludge and primary sludge in the capacity of turf. Findings determined over a two-year study followed suit with numerous articles indicating the need for supplemental nitrogen. However, in cases without supplemental nitrogen (through the addition of fertilizer) it was found that the turf grass grown was still acceptable. While PHP does produce primary sludge which is easily isolated, the likelihood of use on a fresh basis is unlikely as the primary sludge is at a consistency of approximately 3%, fundamentally requiring the transport of water.

2.4 Paper mill sludge in hydroseeding applications

2.4.1 Grass Growth

Grass growth is typically broken into five stages:

- “Germination
- Vegetative
- Elongation
- Reproductive
- Seed Ripening” (Moore *et al.,* 1991)

The vegetative stage requires the root to have developed into the soil layer, mitigating the chance for movement in adverse conditions. The University of Oregon (2018) provides depictions of each stage on their website.

Nutrient considerations must follow Mikkelsen (2011)'s 4 R's, being the "right source, right rate, right time, and right place." To expand, this looks at the source of nutrients, the rate of application, the season of application, and the environment chosen for application.

When considering the applicability for substrates used in grass growth, these stages can be used to identify outcomes and create comparisons. The germination state refers to the initial step of the growth process, which begins with utilization of the seed. This stage in the process can be affected by numerous factors such as environment and growth of material plant; the stresses experienced by the maternal plant can lead to changes in the growth periods/ timing of stages in the product seeds (Mackin *et al.,* 2021). The vegetative stage involves a focus on photosynthesis through increased leaf area; the leaves (Oregon State University, 2018). Tillering is a key part of the vegetative stage, wherein increased leaf area and successful photosynthesis promotes new growth of blades, or 'tillers.'

Elongation, as the name would suggest, follows the tillers as they grow lengthwise. Management within this stage is crucial as perennial grasses are vulnerable to defoliation. In grass the reproductive stage, tillers continue to grow and if one is working with a flowering plant, this is the period in growth where buds would begin to be visible. In grass, this stage may be less noticeable to a viewer, but a flag leaf can appear (Plant and Soil Sciences, n.d.). This leads directly into seed ripening, wherein the caryopsis develops (Moore *et al.,* 1991).

2.4.2 Hydroseeding Process

Hydroseeding began with the mixing of water and seed, specifically for use on sloped or difficult to sod areas. When purchasing sod, the grass comes with a thick layer of soil and root material, which when placed on an incline does not pose an equivalent risk of washaway. This is not to neglect the issues slopes can have on sods however, where stakes are normally required to hold the sods in place until the root systems can grow through into the new soil. An additional method is drill seeding, which as the name would suggest, involved application of seeds directly into the ground to avoid washaway and removal by predators (Haynes, 1997). While effective, this method is time consuming and in large laydown areas proves impractical.

A ‘good’ hydroseeding mixture will allow the material to adhere to the soil surface, mitigate runoff, and allow for deep root growth (root: shoot). One must consider that environment of application, and while hydroseeding is an efficient methodology for seeding, especially in large areas, adherence to inclines is crucial. When seed is sprayed onto the ground, the material it is mixed with is the sole component holding the material on the ground.

The hydroseeding process grew to include 4 main components, a cellulosic mulch mixture, tackifier, fertilizer, and seed.

The tackifier serves the purpose of ‘tacking’ the hydroseed mixture to the area on which it has been sprayed. The tacking agent may be excluded in cases where inclines are not an issue. Considerations in the cost-effective method include the need for biodegradable materials, such as a well-known option, Celumulch. This cellulosic medium in Celumulch is 100% recycled paper, which is biodegradable, but does not mean that there is not room for improvement. Nova Scotia is no stranger to hydroseeding. With numerous well-known companies performing hydroseeding services across the province, for domestic and large-scale projects, while there is not a need for hydroseeding material, there is a chance for a competitive product to change the market.

2.4.3 Requirements for a good hydroseeding mixture

When considering the characteristics of a good hydroseeding mixture one must evaluate the application environment for the following:

- Soil conditions
- Site topography
- Temporal conditions
- Maintenance requirements
- Traffic
- Vegetation types (Michigan Department of Environmental Quality)

This suggests that hydroseeding mixtures can differ based upon the laydown area, which often requires hydroseeding professionals to evaluate and make changes to their mixtures on site.

2.4.4 Limitations to paper mill sludge in hydroseeding applications

PHP's sludge posed two initial concerns, the first being the presence of heavy metals and the second being the presence of a small concentration of fecal coliforms (considering leachate, runoff, and bioaccumulation) from the integration of sanitary sewer into process sewer at the industry site. Selenium, for example, was identified early as a potential metal of concern. Selenium could be introduced into the process stream from the paper making process due to its being a component in the makeup of wood. Selenium can be environmentally harmful in high concentrations (Fu *et al*., 2014). The accumulation of selenium in plant tissues has the capacity to negatively affect “stunting, chlorosis, and fading of leaves, interfering with chlorophyl combination and nitrate accumulation that is generally assumed to occur from selenium levels higher than 1 mg/kg” (Gebreeyessus *et al*., 2019).

2.4.2.1 Potential Treatments

Water dispersible magnetic nanoparticle graphene oxide compounds have been proven effective for the extraction of selenium compared to more common methods of adsorption (Fu *et al.,* 2014). However, the tests conducted in this study indicate that PHP’s sludge does not require additional treatment for removal or reduction of selenium. Removal of sanitary sewers as earlier mentioned can also be implemented easily to divert PHP’s sanitary sewer line from the process sewer line.

Overall, from the results of the study in Chapter 4. PHP’s sludge does not require additional treatment to combat the presence of selenium or other concerning heavy metals. The amounts contained in fresh sludge, upon spreading in a thin layer for application in hydroseeding are diluted to well below regulated amounts.

CHAPTER 3 – MATERIALS AND METHODS

Individual article-style chapters will include information from this chapter.

Three growing sites in Nova Scotia, Canada were utilized for hydroseeding experimentation. The first being a flat, open plain field trial on an industrial site located in Port Hawkesbury (45.5993° N, 61.3568° W) with two ~ 2.14 x 2.14 m^2 plots) from June – August 2019. The second occurred in Antigonish (~45.5993° N, 61.3568° W) from August – September 2022, within individual pans with a normalized investigation area of ~ 0.4 m^2 on a natural, outdoor 3:1 incline, with northwest facing sunlight. The third on an artificial 3:1 incline in a southwest facing greenhouse with natural lighting in Bible Hill, locate at the Dalhousie University Agricultural Campus in Truro (45.3716° N, 63.2641° W), in August 2022. Seed utilized throughout the hydroseeding trials varied between Home Gardener All-Purpose Premium Grass Seed (containing high performing varieties of Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra)*, Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*) for bench-scale applications and a mixture of 40% Creeping Red Fescue, 30% Perennial Ryegrass, and 30% Kentucky Bluegrass (Maritime Green Lawn Seed by Maritime Green) for the field studies hydroseeded by a professional hydroseeding application via a third-party company. Carrot (Carrots, Daucus carrota cv. Nantes Scarlet) and lettuce (*Lactuca sativa* cv. Simpson*)* seeds were purchased from Feeds'n Needs (Truro and Antigonish, Nova Scotia, Canada). Strawberry (*Fragaria × ananassa* cv. Charlotte) were purchased from a nursery, Gray's Greenhouse (Addington Forks, Nova Scotia, Canada).

Fresh pulp and paper mill sludge (pH of approximately 4.7, 30% consistency and 70% moisture content) was obtained from Port Hawkesbury Paper LP (PHP) in Nova Scotia. The sludge materials collected from PHP were obtained in the spring and summer months when the dewatering process is least problematic. The PHP mill is a producer of supercalendered paper (previously newsprint) and utilizes a Thermomechanical Pulping process (TMP). The output sludge compound contains waste from the papermaking process as well as the mill's sanitary sewer. On a dry weight basis, the sludge has an approximate C:N ratio 2241.9, total organic and inorganic carbon respectively represent 42.7 and 3.9% respectively (Dalzell, 2021). A typical N:P:K value is 4:1:1 but varies. For hydroseeding applications, the sludge sample was mixed on a mass percent basis with black earth (Greenhouse Gold) at varied percentages for the indoor and outdoor small scale growth trials. Outputs were compared to a control mixture using a cellulosic additive (CA) called Celumulch (Thermo-Cell, Debert, Nova Scotia, Canada) comprised of 100% recycled newspaper with a temporary green dye additive. In the individual plant trials, actual volumes utilized are found in Table 2.

Table 2 - Actual masses of sludge (wet basis, 70% moisture content) and soil with embedded seed containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum).* All mixtures include 14 g seed. In text mixtures are noted at S-SO with percentages representing sludge.

Mass Sludge (%)	Mass Soil (%)	Mass Sludge (g)	Mass Soil (g)	Mass Celumulch (g)
100	0	91	0	0
90	10	81.90	9.10	0
75	25	68.25	22.75	0
50	50	45.50	45.50	0
25	75	22.75	68.25	0
10	90	9.10	81.90	0
5	95	4.55	86.45	0
0	100	0	91	0
0 (control)	0	0	0	91

Similarly, regarding food plant growth trials, actual masses of sludge and Promix soilless media are found in Table 3.

Table 3 - Actual masses of sludge (wet basis, 70% moisture content) and Promix used for carrot (*Daucus carrota*), lettuce (*Lactuca sativa*), and strawberry (*Fragaria* × *ananassa*) growth trials. Values are represented in text as Sludge-Promix (S-P) (with percentage relating to sludge by mass).

Mass Sludge (%)	Mass Promix (%)	Carrot		Lettuce		Strawberry	
		Mass Sludge (g)	Mass Promix (g)	Mass Sludge (g)	Mass Promix (g)	Mass Sludge (g)	Mass Promix (g)
100	0	1328	0	400	0	1000	0
90	10	1195.2	132.8	360	40	900	100
75	25	996	332	300	100	750	250
50	50	664	664	200	200	500	500
25	75	332	996	100	300	250	750
10	90	132.8	1195.2	40	360	100	900
5	95	66.4	1261.6	20	380	50	950
0	100	0	1328	0	400	0	100

3.1 Bench-Scale Outdoor and Greenhouse Trials - Hydroseeding

Aluminum pans filled with a base layer of black earth (~2.5 cm thick) were topped with seed and sludge/black earth mixtures as presented in Table 3. The application rate of the overall mixture was approximately 5.65 kg/m^2 of fresh material based on recommended rates of application [9]. 105 g of fresh material was added to each pan and seeds were embedded (set mass/ volume of mixture). The mixture was applied evenly over an approximately 2.54 cm layer of compacted black soil. Compaction of the base layer of soil was completed manually with hand-applied pressure of approximately 0.7 kg/cm^2 [12] through simple house scale measure. The pans containing the test mixtures were raised on an incline of 3:1 (horizontal to vertical grade) representing the typical highest incline which could be seen on the side of highways for hydroseeding. Each pan was equipped with a 0.5-cm diameter drainage hole. The indoor and small-scale outdoor trial samples were watered daily with approximately 400 mL of tap water.

The indoor trial test pans were placed into a secondary pan for collection of runoff water for visual examination of seed runoff and water retention. Runoff sampling occurred after 28 days in IT1 and 13 days in IT2.

Indoor and outdoor trials (IT and OT) were conducted twice with 2 replicates with varied/ extended growth durations of each mixture per trial. IT1 and IT2 were run for 4 and 3 weeks, while OT1 and OT2 were run for 4 and 7 weeks.

3.2 Industrial Field Trial - Hydroseeding

The outdoor industrial trial on land at Port Hawkesbury Paper utilized a Hydro Seeder (FiNN T170 by FiNN Corp., Fairfield, Ohio, United States) to spray a 4.572 x 2.14 m^2 cleared land space with 50% of the land space sprayed with a conventional hydroseed mixture of seed, a cellulosic additive, and water, and the remaining half replacing the cellulosic component with paper mill sludge; an additional tackifier was not applied to either side of the focus area. Mixed hydroseed material was sprayed from a 5.08-cm diameter hose due to the presence of sawdust, to avoid plugging, which is atypical for hydroseeding applications, where a 5.08 cm diameter hose can often be utilized. The conventional mixture consisted of ~73 kg of cellulose additive, ~14 kg of seed, and 1,886 kg (~1892 L) of water. Sludge and water were added until a comparable consistency to the cellulosic additive mixture was achieved, with 14 kg of seed remaining consistent. These additions resulted in ~118 kg of sludge and an excess of 1,399 kg of water. The exact ratio was not determined as the adjustments were conducted in the field based on the experience of the hydroseeding technicians. No additional seed was added to the sludge mixture to avoid giving the sludge side a germination advantage. Application rates on the ground were kept consistent at ~5651.05 g/m^2 for both mixtures, resulting in a lower seed density being applied to the sludge-based side.

No manual watering was provided for this trial after the hydroseeding application was completed.

3.3 Chemical Analysis

Complete metals (via EPA3050B, Acid Digestion of Sediments, Sludges, and Soils [13]) and e-coli analysis were conducted through RPC Laboratories in Fredericton, New Brunswick as well as through METH2013 based on EPA6020 for material digestion through Inductively Coupled Plasma-mass Spectrometry (ICP MS) by Maxxam Laboratories (now AGAT) in Sydney, Nova Scotia. Elemental analysis was completed on all samples from the three separate experiments.

Collection of plant tissue as full blades of grass cut from the soil surface occurred in August and September 2022. Samples of 1 to 25 g (all product possible collected) were frozen and kept in sealed plastic bags. Plant tissue analysis was conducted utilizing a Standard Plant Tissue Package determining N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Na. These tests were conducted at the Nova scotia Department of Agriculture Laboratory Services, Bible Hill, Nova Scotia.

Nitrate as N were tested by AGAT (Dartmouth, Nova Scotia, Canada) Laboratories via ion chromatography (INORG-121-6005, SM 4110 B).

General pH of mixtures found in Appendix D were determined using a HoldAll Soil Test Kit which provides a color-based estimate of soil pH.

3.4 Growth Analysis

Qualitative and quantitative observations for hydroseeding work were undertaken for the bench-scale trials through blade counts, blade length, germination rate, and runoff amounts, while blade counts, and germination rate were measured for the industrial trial. Blade lengths were measured pre-harvest (early August – end of September 2022) in bench-scale trials and approximately twice per week for the industrial trial. Runoff and sample cohesion was evaluated through volumetric measurements of water collected and qualitative evaluation of seed and organic debris present. Dried root and shoot masses were obtained from two repetitions of the indoor greenhouse trials to allow for a mass-based root: shoot analysis; root material was manually extracted from the soil-sludge cakes following blade harvest and allowed to dry until soil material could be removed effectively through hand extraction, allowing analysis of root material alone.

Water retention was tested through utilization of 8 g of dry growing material (see Table 2) and then water was added to saturation and the remainder was decanted. This provides the ability of the base mixture to retain water.

Chlorophyll fluorescence indices (plant stress via Fv/Fm) was determined using a handheld Chlorophyll Fluorometer (OS30p+ by Opti-Sciences, Hudson, New Hampshire, United States) and chlorophyll content (greenness) was measured using a Chlorophyll Meter (SPAD 502 Plus, by Spectrum Technologies, Aurora, Illinois, United States). These measurements were taken on both the strawberry and lettuce plants. Carrots were not included in these measurements as they are root vegetables and stems were too thin to extract data using these technologies. Strawberry firmness was measured using a Fruit Firmness Penetrometer (GY-03 by Jacksking, Amazon). An EC 500 ExStik II S/N 252957 multimeter (EXTECH, Nashua, New Hampshire, United States) was used to record pH, salinity, total dissolved solids (TDS) and electric conductivity (EC) of the test soils. These tests took place at the beginning of the study. Soil (growth media) samples were diluted in distilled water at a ratio of 1:2, mixed thoroughly, and left to sit for 24 hours before measurements occurred. All plants received approximately 0.4 L of water per day and were organized in a randomized fashion to mitigate uneven conditions.

Through harvesting of the lettuce, dead leaves were removed, and a fresh weight was taken. Once complete, the leaves were dried for 3 days at 65ºC and weighed, with the difference determining the moisture present.

Harvest of carrots similarly involved measurement of fresh weights followed by dry weights after 3 days of drying at 65ºC.

Strawberry harvest occurred as each berry matured. Physical harvest occurred when the berries were fully red and exhibited some sponginess upon the application of mild pressure, similar to what one would seek prior to consumption. Fresh weights were collected from strawberry samples.

3.5 Statistical Analysis

Microsoft Excel V2302 was utilized to construct graphs while XLSTAT 2023 facilitated two sample t-test analyses comparing measured sample outcomes and base mixture compositions, principal critical analyses, and one way Analysis of Variance (ANOVA) testing. These tests focused on fixed factors of base mixture composition (ex. 25% sludge, 75% Promix). These analyses focused on the determination of statistically significant connections between base mixture composition and various measured quantities such as root length.

3.6 Environmental Conditions

All testing took place in the spring and summer months, between 2019 and 2022. Specific environmental conditions are found within each relevant chapter (4 and 5).

CHAPTER 4 HYDROSEEDING POTENTIAL

The article below will be submitted for consideration to the Journal of Biomass Waste Valorization. Figure and table numbers have been adjusted to fit the flow of this document. Reference style aligns with journal standards.

Paper Mill Sludge as a Replacement for the Cellulosic Component of Hydroseed Mixtures

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4.1 Abstract

Pulp and paper mill sludge is composed of cellulosic waste and clay and rich in microorganisms. . Field and greenhouse studies were carried out to determine if sludge from a case study industry can replace the typical cellulosic additive utilized in hydroseeding applications and the ideal application rate of a sludge-soil-seed mixture. The treatments were 0 - 100% sludge and soil by mass with a consistent mass of embedded seeds (Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra)*, Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Seeding with a top layer of soil with 5 to 75% sludge would be most competitive and comparable to current outcomes using a cellulosic additive after 3 weeks of growth. Mixtures containing 5- 25% sludge should be selected for quickest germination. A small decrease in germination toward the bottom of the sample plates was seen, however, on an incline, root material suggests that sludge does aid in the creation of both root and shoot material.

The initial concern of presence of heavy metals has been resolved lying below regulatory requirements and the cellulosic additive has the capacity to hold retain a higher volume of water but requires 15 times more material by volume. An increase in sludge has the capacity to increase water retention by 20%. The cellulosic additive in hydroseeding applications can be replaced by sludge without plant detriment, however, further testing is needed to determine long-term effects.

4.2 Keywords

Waste Valorization, Pulp and Paper Sludge, Waste Reuse, Industrial Sustainability; Hydroseed

4.3 Highlights

- Paper mill sludge exhibited evidence of slow-release fertilizer behavior.
- Germination rate increased in the presence of slow percentages of sludge by mass.
- Grass demonstrated the capacity to be grown in 100% sludge.
- Paper mill sludge showed potential to replace the typically cellulosic additive in hydroseeding mixtures.

4.4 Graphical Abstract

4.5 Introduction

Valorization of nutrient-rich waste streams is a field of increasing importance as we look to improve landfill-diversion strategies and create integrated industrial economies with reduced environmental impact.

Biosolids from pulp and paper mills, more commonly known as sludge, represents one such opportunity (Fabuert *et al*., 2016). Sludge is currently disposed of using either dewatering and landfilling or dewatering and use as fuel (often with a net negative energy value). Pulp and paper mill sludge is composed of cellulosic waste, clay, microorganisms, and at times, sawdust (MacDonald *et al*., 2018). An alternative valorization pathway that has recently been explored for this solid waste material is use as a soil amendment. O'Brien *et al.,* [1] tested paper mill sludge from a tissue and towel producing industry (utilizing recycled, deinked newspaper through a chemical process) with a local sewage stream included, and soil mixtures with regards to corn (*Zea mays L*.) growth. The findings of that study showed that paper mill sludge provided additional organic content and phosphorous but did not provide sufficient nitrogen, even when supplemented with additional nitrogen. These findings are further supported by Chong & Purvis [2] where nursey grown plants were shown to flourish in aged or composted sludge from deinked newspaper. However, introduction of supplemental nitrogen was suggested.

Sludge waste provides a water-rich organic material equipped with nutrients (Camberato *et al*., 2006, Faubert *et al.,* 2016); however, the presence of heavy metals and a small percentage of bacteria compared to the overall flow rate of material, has the potential to limit end uses (Camberato *et al.,* 2006, Anderson, 2015). Some of the concerns with sludge application on land for aesthetic and agricultural use relates to the risk of exceeding regulatory limits for.metals and the potential for bioaccumulation of inorganic components commonly present in these waste streams when applied in agri-food applications or areas where run-off may lead to contamination of surrounding waterways and soil. Within Canada, a variety of relevant regulations exist for application of sludge in land applications, such as the Canadian Food Inspection Agency (CFIA) fertilizer guidelines [3] and the Canadian Council of Ministers of the Environment (CCME) biosolids regulations [4,5]. CFIA guidelines prohibit an excess of heavy metals (inorganic) or the presence of bacteria (often because of human fecal matter, namely sanitary sewage). For agricultural applications this is especially concerning as consumption of products, such as food crops, in contact with such sludge is often expected. Such a concern could require diversion of the bacterial carrying stream (sanitary sewer) if currently integrated within the biosolids process pathway of a pulp and paper operation. CCME guidelines for compost quality are divided into Class A and Class B. Class A allows more liberal use of biosolids, depending on the presence of trace metals, while Class B often requires additional treatment or regulated application. Materials which do not fall under Class A or B are required to be disposed of [4,5]. Ideally, pulp and paper sludge would meet Class A definition by Nova Scotia government regulations [4,5]. Such regulations for land application (based upon municipal biosolids – more storage and/or capping focused) could be comparative for agricultural use [6]. Using the material on an industrial, business scale would require approval from, in Nova Scotia, the Department of Environment.

The potential exists to consider paper mill sludge use on land in Nova Scotia, with a case focus on the sole operating paper mill within the province, Port Hawkesbury Paper LP. This paper mill currently utilizes on-site landfilling for storage or incineration for disposal methodology. There are limited studies exploring the applicability of paper mill sludge for land-based soil amendment within the context of these regulations, and there is potential to explore alternative applications. Within Class A applications specifically, under CCME guidelines, the potential for use of pulp and paper mill sludge in hydroseeding applications was investigated.

As an alternative to purchasing sod, hydroseeding is considered a cost-effective option for grass growth [7]. Hydroseeding is a commonly used process for seeding surfaces, known not only for its aesthetically pleasing outcome and simplicity of application, but also for post-construction cleanup through stabilization of the roadside and habitat restoration and stabilization of recent roadside environments and habitat restoration [8]. The process utilizes a mixture of cellulosic material, tacking agent, seed and water that is sprayed evenly across a surface, with typical ratios of approximately 173:14:11 kg (cellulose-seed-fertilizer) combined with 1893 L of water; [9]. The typical cellulosic material utilized is finely shredded newspaper, as a biodegradable additive allowing for cover to be given to the seeds, while also providing a point of adherence or connection to soil while awaiting germination. Additionally, a superabsorbent has been utilized in combination with the cellulosic fiber in hydroseeding practices to aid in irrigation practices, creating a hydrogel that holds water for use during the day or when water is scarce [8].

Pulp and paper mill sludge has the potential to replace the cellulosic component utilized in hydroseeding mixtures while providing additional benefits for water retention, nutrient loading, and tacking ability. This raw, moisture rich sludge can be abundant in phosphorous, nitrogen, and iron, while having a carbon to nitrogen ratio of over 2000 [10]; notably, sludges produced in various paper mills have variable levels of nutrients and metals. The high nitrogen value presented is not indicative of all potential samples. Chemical additives, such as polymer and coagulant from the dewatering process may also provide seed and soil stabilization similar to tackifiers.

A gap in literature exists in identifying the potential for pulp and paper mill sludge use in hydroseeding applications. Although studies have been conducted to evaluate the impact of pulp and paper biosolids application on plant growth, [1, 10], the use of this sludge in grass growth, specifically hydroseeding, has not been investigated. The focus of this study was to examine the applicability of pulp and paper mill sludge in place of the typical cellulosic additive for hydroseeding application on areas such as along highways. The specific objectives of the study were to determine if pulp and paper sludge can replace the typical cellulosic additive utilized in hydroseeding applications. If so, what is the ideal application rate? Additionally, properties of runoff, water retention, stability on incline planes, and bioaccumulation were foci. The sludge product used in this study is also notably developed from a Thermomechanical Pulping (TMP) process.

4.6 Materials and Methods

4.6.1 Study Sites

Three growing sites in Nova Scotia, Canada were utilized for the study. The first being a flat, open plain field trial on an industrial site located in Port Hawkesbury (45.5993° N, 61.3568° W) with two ~ 2.14 x 2.14 m^2 plots) from June – August 2019. The second occurred in Antigonish (~45.5993° N, 61.3568° W) from August – September 2022, within individual pans with a normalized investigation area of ~ 0.4 m^2 on a natural, outdoor 3:1 incline, with northwest facing sunlight. The third on an artificial 3:1 incline in a southwest facing greenhouse with natural lighting in Bible Hill at the Dalhousie University Agricultural Campus in Truro (45.3716° N, 63.2641° W), in August 2022. All trials took place without the addition of chemical treatments such as the use of fertilizers, pesticides, etc. and occurred during the summer months (between July and October). Abiotic conditions during the period of the outdoor trials are provided in Appendix 4A.

4.6.2 Sample Details

Fresh pulp and paper mill sludge (pH of approximately 4.7, 30% consistency and 70% moisture content) was obtained from Port Hawkesbury Paper LP (PHP) in Nova Scotia. The sludge materials collected from PHP were obtained in the spring and summer months when the dewatering process is least problematic. On a dry weight basis, the sludge has an approximate C:N ratio 2241.9, total organic and inorganic carbon respectively represent 42.7 and 3.9% respectively (Dalzell, 2021). A typical N:P:K value is 4:1:1 but varies. The PHP mill is a producer of supercalendered paper (previously newsprint) and utilizes a TMP process. The output sludge compound contains waste from the papermaking process as well as the mill's sanitary sewer. The sludge sample was mixed on a mass percent basis with black earth (Greenhouse Gold) at varied percentages for the indoor and outdoor small scale growth trials (Table 4). Outputs were compared to a control mixture using a cellulosic additive (CA) called Celumulch (Thermo-Cell, Debert, Nova Scotia, Canada) comprised of 100% recycled newspaper with a temporary green dye additive.

All sample requirements (apart from pulp and paper mill sludge and Celumulch) are commercially available.

Table 4 - Actual masses of sludge (wet basis, 70% moisture content) and soil with embedded seed containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). All mixtures include 14 g seed. In text mixtures are noted at S-SO with percentages representing sludge.

Mass Sludge (%)	Mass Soil (%)	Mass Sludge (g)	Mass Soil (g)	Mass Celumulch (g)
100	0	91	0	0
90	10	81.90	9.10	0
75	25	68.25	22.75	0
50	50	45.50	45.50	0
25	75	22.75	68.25	0
10	90	9.10	81.90	0
5	95	4.55	86.45	0
0	100	0	91	0
0 (control)	0	0	0	91

Seed utilized throughout the trials varied between Home Gardener All-Purpose Premium Grass Seed (containing high performing varieties of Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra)*, Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*) for bench-scale applications and a mixture of 40% Creeping Red Fescue, 30% Perennial Ryegrass, and 30% Kentucky Bluegrass (Maritime Green Lawn Seed by Maritime Green) for the field studies hydroseeded by a professional hydroseeding application via a third-party company.

4.6.3 Bench-Scale Outdoor and Greenhouse Trials

Aluminum pans filled with a base layer of black earth (~2.5 cm thick) were topped with seed and sludge/black earth mixtures as presented in Table 4. The application rate of the overall mixture was approximately 5.65 kg/m^2 of fresh material based on recommended rates of application [9]. 105 g of fresh material was added to each pan and seeds were embedded (set mass/ volume of mixture). The mixture was applied evenly over an approximately 2.54 cm layer of compacted black soil. Compaction of the base layer of soil was completed manually with hand-applied pressure of approximately 0.7 kg/cm^2 [12] through simple house scale measure. The pans containing the test mixtures were raised on an incline of 3:1 (horizontal to vertical grade) representing the typical highest incline which could be seen on the side of highways for hydroseeding. Each pan was equipped with a 0.5-cm diameter drainage hole. The indoor and small-scale outdoor trial samples were watered daily with approximately 400 mL of tap water. The indoor trial test pans were placed into a secondary pan for collection of runoff water for visual examination of seed runoff and water retention. Runoff sampling occurred after 28 days in IT1 and 13 days in IT2.

Indoor and outdoor trials (IT and OT) were conducted twice with 2 replicates of varied/ extended growth durations of each mixture per trial. IT1 and IT2 were run for 4 and 3 weeks, while OT1 and OT2 were run for 4 and 7 weeks.

4.6.4 Industrial Field Trial

The outdoor industrial trial on land at Port Hawkesbury Paper utilized a Hydro Seeder (FiNN T170 by FiNN Corp., Fairfield, Ohio, United States) to spray a 4.572 x 2.14 m^2 cleared land space with 50% of the land space sprayed with a conventional hydroseed mixture of seed, a cellulosic additive, and water, and the remaining half replacing the cellulosic component with paper mill sludge; an additional tackifier was not applied to either side of the focus area. Mixed hydroseed material was sprayed from a 5.08-cm diameter hose due to the presence of sawdust, to avoid plugging, which is atypical for hydroseeding applications, where a 5.08 cm diameter hose can often be utilized. The conventional mixture consisted of ~73 kg of cellulose additive, ~14 kg of seed, and 1,886 kg (~1892 L) of water. Sludge and water were added until a comparable consistency to the cellulosic additive mixture was achieved, with 14 kg of seed remaining consistent. These additions resulted in ~118 kg of sludge and an excess of 1,399 kg of water. The exact ratio was not determined as the adjustments were conducted in the field based on the experience of the hydroseeding technicians. No additional seed was added to the sludge mixture to avoid giving the sludge side a germination advantage. Application rates on the ground were kept consistent at ~5651.05 g/m^2 for both mixtures, resulting in a lower seed density being applied to the sludge-based side.

No manual watering was provided for this trial after the hydroseeding application was completed.

4.6.5 Chemical and Component Analysis

Complete metals (via EPA3050B, Acid Digestion of Sediments, Sludges, and Soils [13]) and e-coli analysis were conducted through RPC Laboratories in Fredericton, New Brunswick as well as through METH2013 based on EPA6020 for material digestion through Inductively Coupled Plasma-mass Spectrometry (ICP MS) by Maxxam Laboratories (now AGAT) in Sydney, Nova Scotia. Elemental analysis was completed on all samples from the three separate experiments.

Collection of plant tissue as full blades of grass cut from the soil surface occurred in August and September 2022. Samples of 1 to 25 g (all product possible collected) were frozen and kept in sealed plastic bags. Plant tissue analysis was conducted utilizing a Standard Plant Tissue Package determining N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Na. These tests were conducted at the Nova scotia Department of Agriculture Laboratory Services, Bible Hill, Nova Scotia.

4.6.6 Experimental Design

Bench-scale indoor and outdoor samples occurred with two replicates of varied/ extended growth durations of each mixture of sludge and soil. Actual masses of sludge, seed, soil, and cellulosic additive (control) are found in Table 1. Mixtures from Table 1 were hand stirred in an aluminum pan and then poured over top of the base soil layer. Greenhouse samples were placed on an artificial 3:1 incline while outdoor samples were placed on a natural 3:1 incline. Replicates were placed parallel to each other.

4.6.7 Growth Analysis

Qualitative and quantitative observations were undertaken for the bench-scale trials through blade counts, blade length, germination rate, and runoff amounts, while blade counts, and germination rate were measured for the industrial trial. Blade lengths were measured pre-harvest (early August – end of September 2022) in bench-scale trials and approximately twice per week for the industrial trial. Runoff and sample cohesion was evaluated through volumetric measurements of water collected and qualitative evaluation of seed and organic debris present. Dried root and shoot masses were obtained from two repetitions of the indoor greenhouse trials to allow for a mass-based root: shoot analysis; root material was manually extracted from the soil-sludge cakes following blade harvest and allowed to dry until soil material could be removed effectively through hand extraction, allowing analysis of root material alone.

Transfer factors (TF) were determined through dividing the concentration of an analyte in the output product (grass blades) by the concentration of the same analyte in the base soil mixture.

Water retention was tested through utilization of 8 g of dry growing material (see Table 1) and then water was added to saturation and the remainder was decanted. This provides the ability of the base mixture to retain water.

4.6.8 Statistical Analysis

Microsoft Excel V2302 was utilized to construct graphs while XLSTAT 2023 facilitated two sample t-test analyses comparing measured sample outcomes and base mixture compositions and one way Analysis of Variance (ANOVA) testing. These tests considered fixed factors of base mixture composition and considered changes in measured qualities.

4.6.9 Environmental Conditions

With sampling and testing taking place in the spring – summer months, seasonal data (fall and spring) can be found in Appendix A.

4.6.10 Seasonal Considerations

Pulp and paper mill sludge characteristics change seasonally, with values in this study relating to minimal addition of dewatering chemicals. The winter months present a challenge due to the increased presence of filamentous algae on settling tanks linked to nutrient deficiencies [14,15]. During the winter months the Mixed Liquor Suspended Solids (MLSS), Biological

Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) [14, 15], become difficult to regulate due to the nutrient deficiencies. However, PHP's effluent is regularly monitored for environmental safety, suggesting changes would be a non-issue for toxicity concerns.

4.7 Results and Discussion

4.7.1 Bench-Scale Outdoor and Greenhouse Trials

The progression of the indoor bench-scale greenhouse trials is presented in Figure 3. Specifically, the first trial (IT1), where the second (IT2) followed a similar pattern of growth, apart from first sight of growth being one week behind IT1. Following one week of growth, in the first trial (IT1), low-mid-range concentrations of sludge (5 - 25%) produced the quickest time to germination. The one-week difference in seedling emergence was prevalent through the remainder IT2 and at the 3-week post-plant point, all mixtures began to accumulate density of growth. The control (100% Cellulose Additive (CA) sample) became noticeably sparse compared to the other test mixtures after 4-weeks, suggesting that the absence of nutrients in this soil matrix impacted plant growth and soil amendment with fertilizer would be required. Upon conclusion of both trials, the blade length increased with increasing sludge percentage.

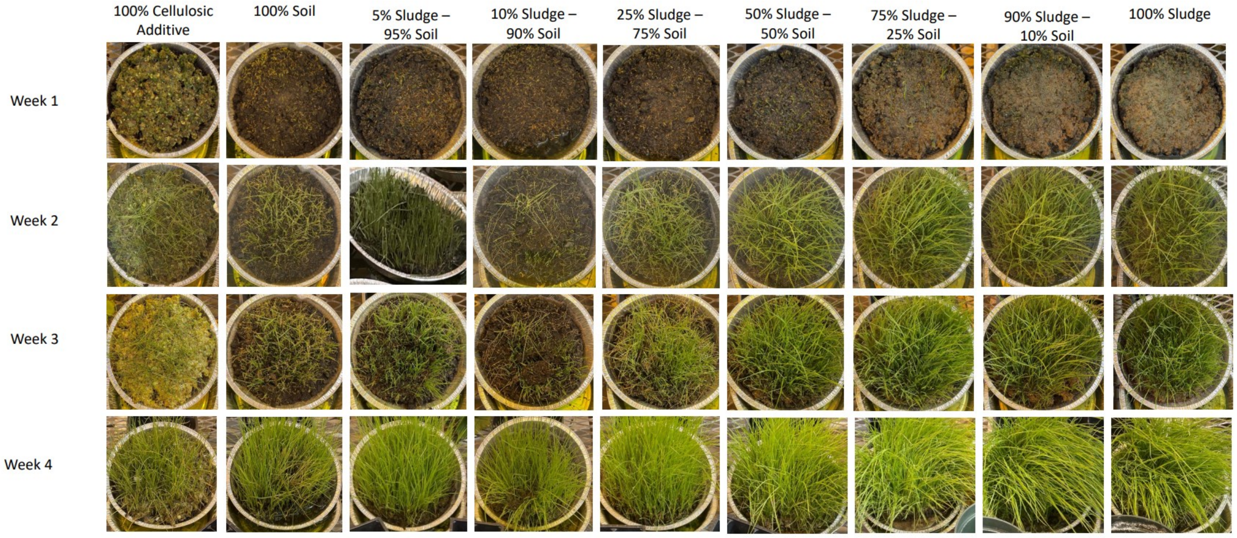

Figure 3 - Indoor trial 1 weekly grass growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

The sludge mixture was found to adhere well to the underlying soil mixture, except in the cases of the highest sludge concentrations (50 - 100% S-SO) where some release was observed toward the lower portion of the pan on the incline. This suggests that with increasing sludge percentage seeds are not as tightly held within the material and can be washed away. This could also be due to the restricted ability of the containers to drain due to the small hole present, where some pooling was observed near the bottom of the incline shortly after watering. While not persistent, this could have contributed to detachment of the seed and sludge layer in this area.

Concurrently to the indoor trials, outdoor trials took place on a natural incline with results displayed in Figure 4, specifically for OT2, with OT1 following a similar pattern of growth. The outdoor trials showed notable growth after the first week compared to the indoor trials; the quickest, densest growth occurred in mixtures containing 10 to 25% S-SO.

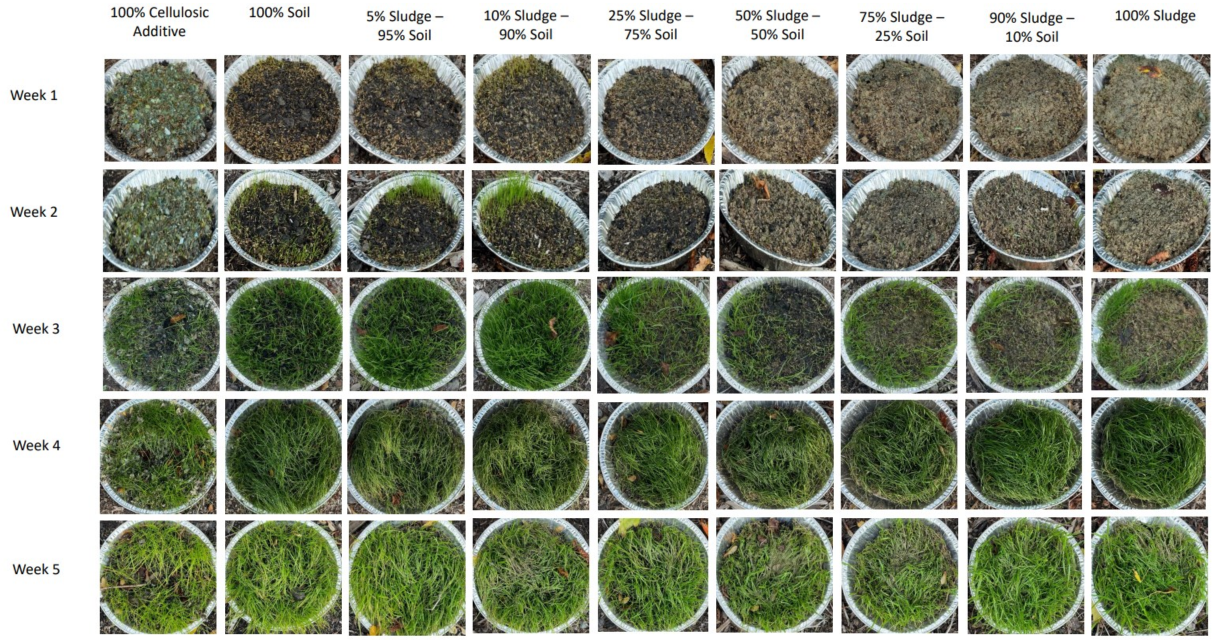

Figure 4 - Outdoor trial 2 weekly grass growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Upon completion of the indoor trials, the longest blade length was found to be in the test pans containing 90 and 100% S-SO (Figure 5), but the densest coverage remained in the low-mid percentages (5 – 10% S-SO) of sludge; these compete with the CA mixture typically used in hydroseeding application, producing dense growth. Water retention was observed to be higher in the CA and 90 to 100% S-SO mixtures, which was expected given the historical difficulty in dewatering paper mill sludge [14, 15]; the increased presence of cellulosic material and the ability to bind water molecules would cause the increase in ability to retain water. At two weeks of growth the results are statistically significant, relating blade length and percentage sludge inclusion ($p < 0.05$). The trend discontinues beyond two weeks.

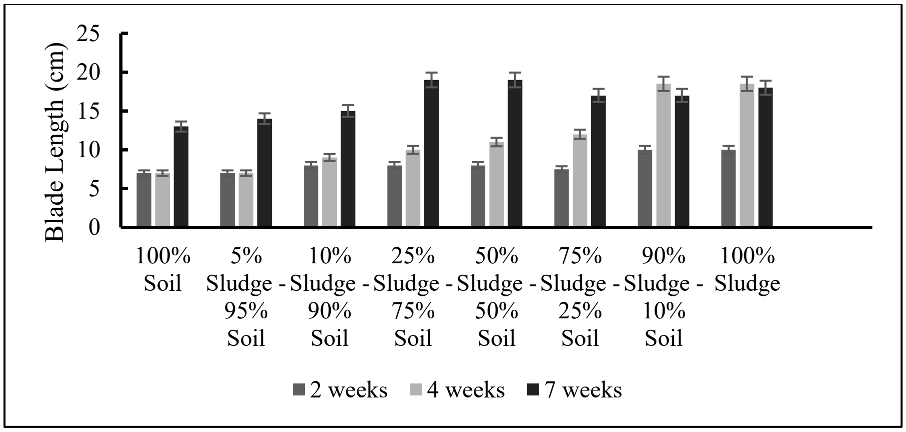

Figure 5 - Average blade length over varied amendment mixtures and weeks of testing of samples containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and Lolium *multiflorum*). Error bars indicated in percentage.

Figure 5 demonstrates blade counts over each week of growth, with averaged values from two replicates of varied/ extended growth durations of the indoor and outdoor trials. The maximum value counted is 100 blades. More than 3 weeks are needed to meet the 100-blade count for mixtures containing more than 50% S-SO. These plots further support, as with the previous figures, that low-mid range concentrations of sludge are most effective for increasing initial germination rates. The data presented in Figure 6 illustrates that the 100% soil (with embedded seed), 5,10, and 25% S-SO mixtures germinated quickest in both the indoor and outdoor trials. 3 weeks post plant, all mixtures quickly caught up, and those mixtures containing higher percentages of sludge produced noticeably longer blades of grass. In week 7 of the outdoor bench-scale trials (Figure 3), the 75, 90, and 100% S-SO mixtures exhibited sparsity in remaining blades. The connection between percentage of sludge and numbers of blades is inconsistent and not a statistically significant pattern.

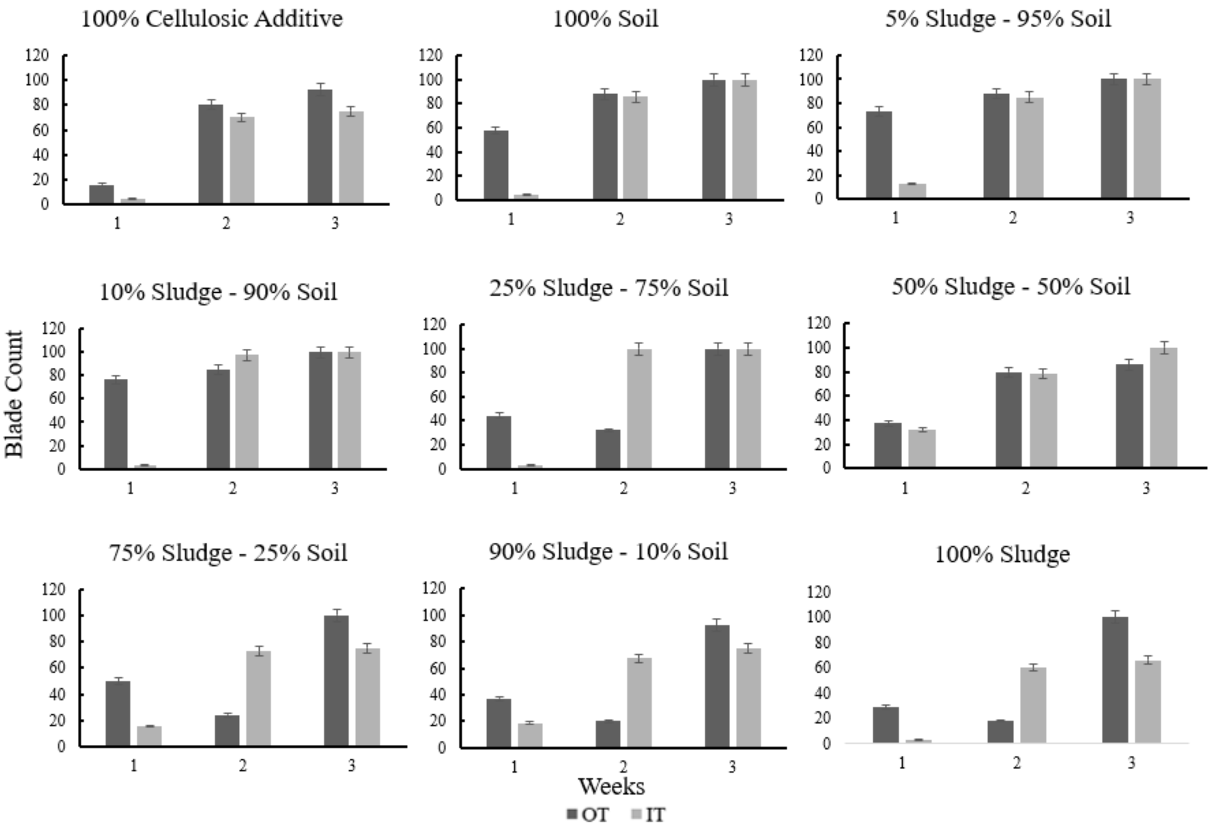

Figure 6 - Average relative blade count for indoor and outdoor small-scale growth trials beginning 1 week post plant containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne and Lolium multiflorum*). Error bars indicated in percentage.

4.7.1.2 Root:Shoot Estimate

Qualitative analysis indicated that the roots of all mixtures penetrated the base layer of soil in the test pans, creating stong adhereance with the ground (as the ground represents the base layer of soil). This is important in hydroseeding considerations, especially on inclined surfaces.

Photographs of the root systems of the indoor hydroseeding bench-scale trials taken after weeks

4 (IT1) and 3 (IT2) are presented in Figure 7.

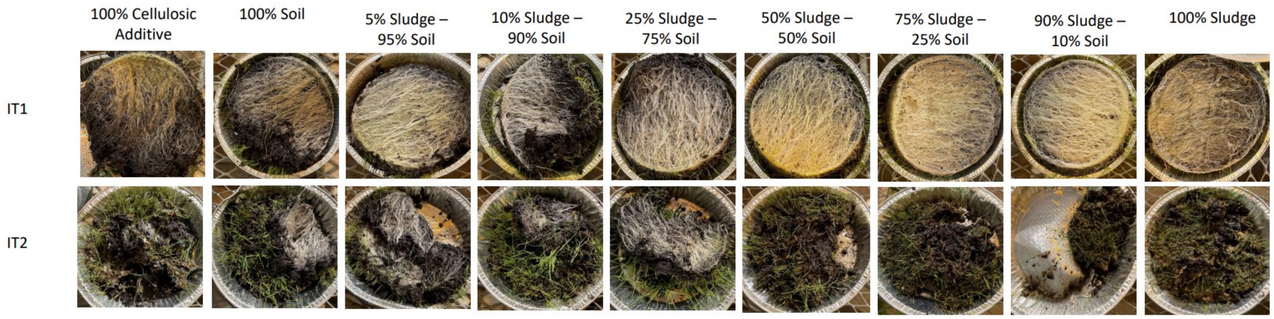

Figure 7 - Indoor hydroseeding trials; view of root system from base of samples grown in media containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*).

Mixtures with increased percentage of sludge in the IT2 study were found to break down when handled (Figure 7). This would suggest that mixtures containing high percentages of sludge create an additional layer of material which roots must penetrate prior to connecting directly with soil; this is supported by the addtitional time, 4 weeks in IT1 vs. 3 weeks in IT2) required for development of a dense root system (Figure 7).

Figure 8 presents the masses of grass, roots and root to shoot ratio (e.g., material above ground [17]) for all mixtures in IT1. The 5% sludge sample was found to result in the highest root:shoot value. The trend indicates a decrease in root:shoot ratio with increasing percentage of sludge. Increasing sludge percentage also aligns with increasing shoot (grass blade) presence, which while aesthetically pleasing, in an incline space, could prove detrimental without stable penetration into the soil base layer. Slight variation in results could be due to the blade material being fresh matter (post-harvest/ pre-drying) while the root material has been air-dried, this could create inconsistencies in mass. However, the trends exhibited from both lines are similar, suggesting that at higher sludge percentages, a greater amount or density of blades is produced, and the roots are more prominent, indicating a system which will adhere to the ground effectively, meaning that the roots will be deeper into the soil.

Root: shoot ratios are directly relevant to the percentage of sludge within a mixture ($p < 0.05$) showing statistical significance. However, the direct relationship between percentage of sludge and grass or root mass is not significant via a t-test.

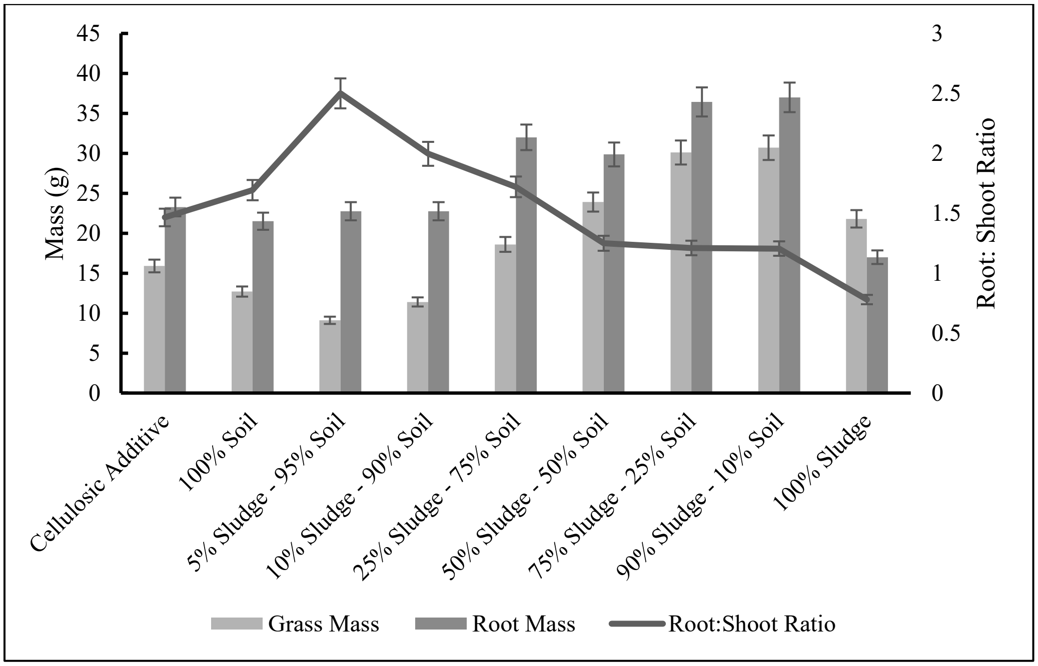

Figure 8 - Root: shoot ratio for indoor grass trials (left vertical axis) versus grass and root mass (right vertical axis). Samples containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra),* Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Imprecision Uncertainties u (root mass) = ±1 g. Error bars indicated in percentage. N = 3.

An ANOVA analysis was undertaken with results presented in Table 5, showing significant positive correlations between root: shoot values and grass mass produced, due to their low p-values. These two characteristics also showed potential for near-linear alignment with R^2 values above 0.5.

Table 5 - Analysis of Variance (ANOVA) statistics root: shoot analysis of samples containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra),* Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*).

	Source	DF	Mean squares	F	P-value	R^2
Root:Shoot	Model	1.000	1.301	11.775	**0.011**	0.627
	Error	7.000	0.110			
	Corrected Total	8.000				
Grass Mass	Model	1.000	355.933	17.783	**0.004**	0.718
	Error	7.000	20.016			
	Corrected Total	8.000				
Root Mass	Model	1.000	52.870	1.059	0.338	0.131
	Error	7.000	49.906			
	Corrected Total	8.000				

4.7.2 Industrial Trials

Following hydroseeding, photographs of the growth plots used in the land-based trial are presented in Figure 9 (after 12 days), and a close-up of the area near the center of each plot after 25 days (Figure 10). The dark area on the cellulose additive (CA) plot is from dye added in the CA mixture. No maintenance was provided to this laydown area following hydroseed application.

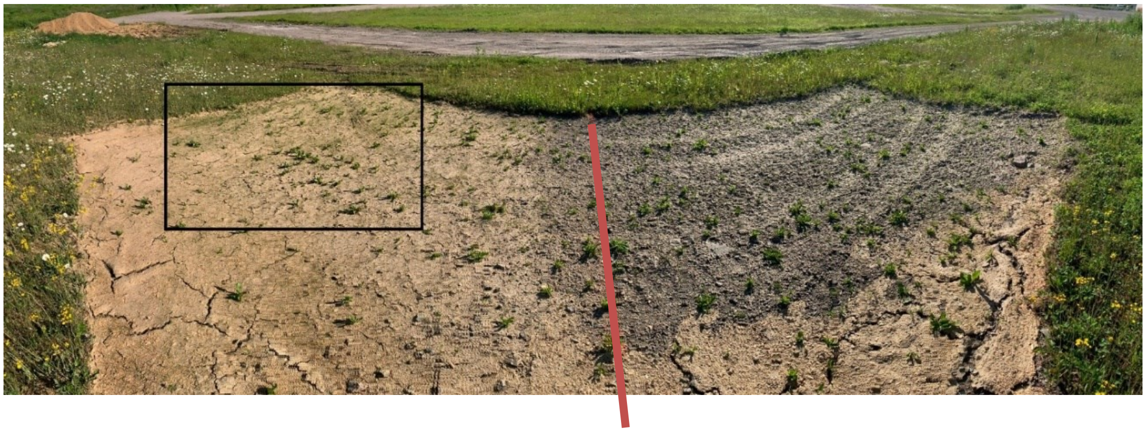

Figure 9 - Panoramic view of 15 x 7 ft study area with orange line dividing sludge test side using 100% sludge with embedded seed (left) and Celumulch test side (right) using 100% Celumulch and embedded seed after 12 days. Both sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Figure 10 - Grass follicles present 25 days post hydroseed application: left representing the sludge test side and right representing the Celumulch test side. Both contain embedded seed with 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

During the trial, measurements of blade counts were conducted within marked areas (Figure 13). Figure 11 provides grass follicle counts for both hydroseed mixtures over this period, with the sludge test mixture exhibiting a significantly higher density of grass follicles compared to the CA test side, despite the loading of mass of grass seed per unit volume in the mixture applied being lower. The exhibited speed of growth and density of coverage of the sludge test side was shown in this study to exceed that of a typical hydroseeding mixture (Figure 10), over the 25-day test period of this study. The p value indicates significant differences between the two test plots in the industrial trial.

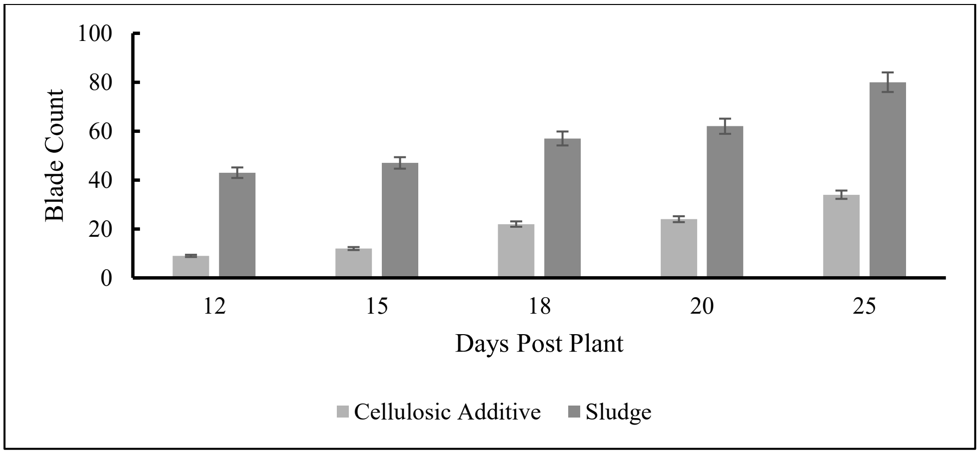

Figure 11 - Growth tracking for Celumulch based hydroseed mixture versus sludge hydroseed mixture ($p > 0.05$). Both sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*). Error bars indicated in percentage.

While a tacking agent was not used on either side of the laydown area upon harvest of blades of grass, roots were embedded in the soil layer rather than the sludge/ hydroseed layer, which supports the long-term growth seen in the IT1 and OT1.

4.7.3 Metals and Nutrient Results

Table 6 indicates the potential for PHP's sludge to be utilized as a biosolids fertilizer. Given that mixtures containing 100% CA, soil, and sludge lie below Class A and B regulations, the risk of bioaccumulation of heavy metals is negligible. Base mixture readings indicate presence of metals in the original mixtures obtained at the time of planting, prior to seeding, and all other samples provide results post harvest (blades of grass). Additional studies have taken place to determine the ability for recycled newspaper and waste in the presence of sawdust for animal bedding, found metals concentrations to be below that of concern for animal exposure [11] this further supports reduced concern for bioaccumulation.

Table 6 - Government residual regulations in comparison to PHP sludge analyte ranges for indoor and outdoor bench-scale trials (adapted from [16]) containing Kentucky Bluegrass (Poa pratensis), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*)

Analyte	Average PHP Residual Analysis *2015 basis (mg/kg)	100% Sludge (base mixture) (mg/kg)	100% Cellulosic Additive (mg/kg)	100% Soil (mg/kg)	CCME Compost & NS Biosolids Class A (MAX) (mg/kg)	CCME Compost & NS Biosolids Class B (MAX) (mg/kg)
Arsenic	-	<1	0.05 - 0.07	0.02 - 0.11	12	75
Cadmium	-	0.12	0.006 - 0.025	0.005 - 0.027	3	20
Chromium	3	4	<0.2 - 0.4	<0.2	210	1060
Cobalt	-	0.2	0.04 - 0.11	0.02 - 0.06	34	150
Copper	3	5	1.3 - 5.2	1.3 - 1.8	400	760
Lead	0.7	1.2	0.05 - 0.39	<0.02 - 0.1	150	500
Molybdenum	-	1	0.12 - 0.31	0.13 - 0.42	5	20
Nickel	-	<1	0.3 - 0.4	<0.2 - 0.5	62	180
Selenium	0.0	<1	<0.2	<0.2	2	14
Zinc	18	12	6.3 - 15.8	6.7 - 12.9	700	1850

Literature review on newspaper for growth applications indicates negligible nutrient availability of nitrogen and phosphorous (0.11% and 0.03%), indicating minimal presence of valuable nutrients [11]. The pH of newspaper, 6.4, which is slightly acidic is higher than that of pulp and paper sludge, ~ 4.74 which is slightly acidic [14] and conducive to ideal growth conditions but does not compete nutrient-wise with sludge-based mixtures.

Throughout all bench-scale trials, samples containing high percentages of sludge showed late germination but quickly caught up and surpassed other mixtures over the duration of the experiments when in the seedling stage. This suggests the potential of slow-release nutrient behaviour. Slow-Release Fertiziliers (SRF) are typically controlled soil additives utilized to allow leaching of nutrients into soils and plants over time, removing the requirement for repetetive fertilization [17,18,19]. Where the grass grown in high percentages of sludge was thick and long (blade length) this would suggest that nutrients are available, as in typical mixtures, but that they are released at a later time. Without SRF behaviour, valuable nutrients may be lost and wasted. PHP's sludge was determined in previous work [14, 15] to have tightly bound water molecules which required rupturing through the addition of acid via direct injection acidification [14]. This phenomena along with the insoluble nature of the cellulosic material present in the sludge may provide slow release of nutrients when used as a soil ammendment.

The transfer factor of a soil-grass test indicates the uptake of heavy metals. This factor is a ratio of the mass of metals in the product divided by metals present in the soil media [20]. Yan *et al.* [20] conducted a review of heavy metals commonly present along roadsides, which creates an ideal comparison for the soils utilized in the study. The presence of heavy metals in soil can affect the surrounding eco-system, leaching into the grass and into animals who ingest the grass [21]. The work conducted by Yan *et al.*, [20] suggests that the uptake of heavy metals into grass is not easily predicted, however, experimental results indicate that there can be an increase in ease of uptake from soil to grass zinc, copper, and lead.

Table 7 shows that small TF values were realized in the sludge mixtures evaluated in this study, demonstrating that there was minimal uptake of heavy metals into the grass grown in sludge ammended mixtures.TF values greater than 1 indicate a greater concentration of analyte in the product than is found in the soil/ component providing feed. TF values for zinc, copper, and lead did not align with Yan *et al.*'s [20] study as these values were below 1. The percentage sludge in this mixutre was 25%, meaning that a higher concentration of metals would be present within a 100% sludge base mixtures. Based upon the metals concentrations present in pure sludge (Table 6) compared to 25% S-SO the expected concentrations in mixtures containing less than 100% sludge would not pose concern regarding regulatory limits. This would suggest that, apart from rubidium, potassium, and sodium, even in the case of utilizing 100% sludge for the base growth mixture, the TF values would remain under 0.05 or 5% of the original nutrient. The increased presence of Rubidium, Potassium, and Sodium are potentially due to mineral and degredation.

Table 7 - Transfer factors (TF) for samples grown in 25% sludge – 75% soil mixtures. Samples contain seed with 40% Creeping Red Fescue (*Festuca rubra),* 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Analyte	**IT**	**OT**	**Average**	**TF Values from Yan *et al.*, Study [20]**
Aluminum	0.011	0.030	0.021	
Barium	0.163	0.378	0.270	
Boron	0.224	0.150	0.189	
Cadmium	0.058	0.121	0.0900	1.340
Calcium	0.060	0.118	0.089	
Cobalt	0.050	0.050	0.050	
Copper	0.043	0.064	0.054	0.470
Iron	0.020	0.040	0.030	
Lead	-	0.026	0.0131	0.180
Lithium	0.042	0.092	0.067	
Magnesium	0.156	0.315	0.235	
Manganese	0.032	0.045	0.038	
Molybdenum	0.139	0.369	0.254	
Nickel	0.250	0.300	0.275	
Potassium	2.741	2.692	2.716	
Rubidium	2.261	3.682	2.971	
Sodium	1.162	1.526	1.344	
Strontium	0.234	0.398	0.316	
Vanadium	-	0.050	0.025	
Zinc	0.186	0.363	0.274	0.630

4.7.4 Seasonal Considerations

A series of samples were tested with results presented in Figure 12. This figure is limited to metals which showed a notable change between months. A greater amount of acid and polymer and coagulant are injected into PHP's sludge in the colder months to combat the formation of filamentous algae and increase dewaterability [14]. Aluminum appeared most greatly affected by seasonal change. However, this study's experiments yielded the highest concentrations of aluminum compared to other seasons where data was collected. Aluminum can be directly linked to the usage of dewatering chemicals as a key makeup component which can be attributed to the removal of sawdust from PHP's typical sludge output, which requires additional chemical support.

Considering both bars in Figure 12, all metal levels across seasons lie below those of the recent 2022 study, indicating no concern for use in grass growth. Additionally, with the hydroseeding predominantly occurring in the warmer months, the 2022 study adequately represents a typical mixture to be used in this process and seasonal variation presents negligible risk.

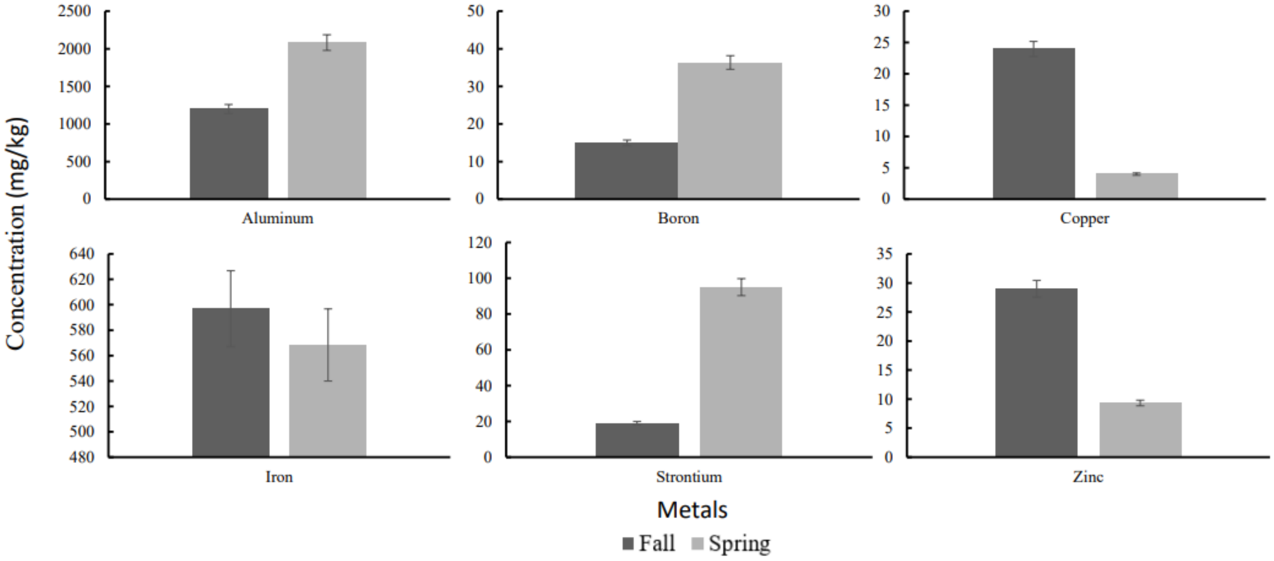

Figure 12 - Seasonal metals comparisons for Port Hawkesbury Paper's sludge product. Error bars indicated in percentage.

4.7.5 Run-off analysis

Runoff amounts in Figure 13 on average are greater in IT1; this appears to relate to either absorption and retention of water in mixtures or degradation of cellulosic material, which would reduce available matter for water absorption. An ANOVA test considering IT1 and IT2 revealed that IT2 had a positive correlation with the percentage of sludge included in the growth medium, while IT1 did not; this determination was made via p-values.

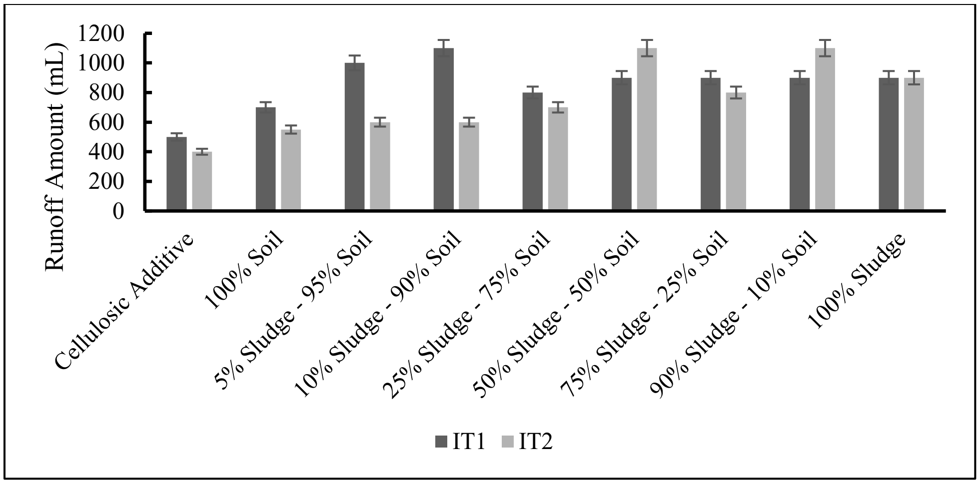

Figure 13 - Runoff volumes over varied amendment compositions from a single 1000mL watering. Error bars indicated in percentage ($p < 0.05$). Samples contain seed with 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Figure 14 presents information on water retention qualities of the base mixture material. The CA sample was shown to hold a significantly greater volume of water than all other samples, proving superior in water retention properties. The increased percentage of sludge resulted in increased water retention by almost 20% compared to soil alone.

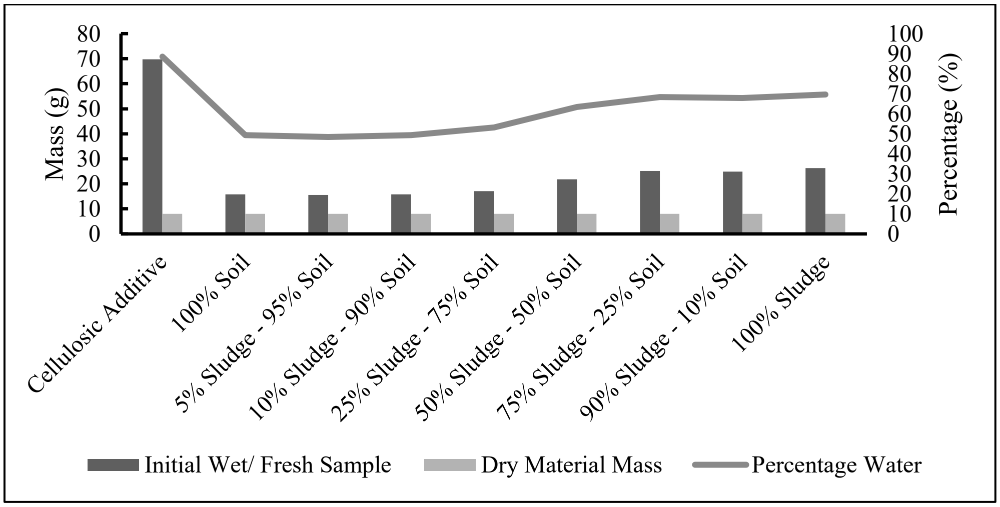

Figure 14 - Ability of mixtures to retain water following saturation ($p > 0.05$). Samples contain seed with 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Additionally, the volume of CA required to meet the common mass value of 20 g exceeded the physical volumes of both sludge and soil. Approximately 15 times more CA is needed on a volume basis in comparison to sludge.

4.8 Conclusions

Pulp and paper mill sludge has the potential to act as an effective replacement for the cellulosic additive in hydroseeding applications. 100% sludge can fully replace any supplementary soil material, however, considering qualitative and quantitative data, mixtures of soil with 5-75% sludge would be most competitive and comparable to current outcomes using a CA after 3 weeks of growth. Mixtures containing 5- 25% sludge should be selected for quickest germination. A small decrease in germination toward the bottom of the sample plates was seen in all mixtures, however, on an incline, root material suggests that sludge does aid in the creation of both root and shoot material.

The initial concern of presence of heavy metals has been resolved, with transfer factors being in most cases negligible, but most importantly, the values lie below CCME and CFIA regulations through hydroseeding application in a thin layer. Considering the nutrients in the sludge there is the potential for slow release to occur, which lends itself to the delayed, but quick growth of grass in mixtures containing high percentages of sludge.

4.9 Acknowledgements

We wish to acknowledge the support of Joe Parsons and Highland Landscaping throughout the preliminary trials and continued work. Port Hawkesbury Paper is acknowledged as a long-term research supporter and funding source. We would also like to recognize the support from a Mitacs Accelerate Grant – IT32158 - Paper mill biosolids reuse through integration into hydroseed mixtures.

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4.11 Appendix 4A Environmental Conditions

Abiotic conditions were considered for all 3 trials, were considered and are presented in Figs. 15-18. These graphs feature weather data from stations nearby to the site. Fig. 15-16 depcits weather data for Antigonish, Nova Scotia, where grass was grown in a residential area of a natrual 3:1 slope. High volumes of precipitation were seen in the outdoor trials nearing the start of OT2 and the end of OT1 and OT2.

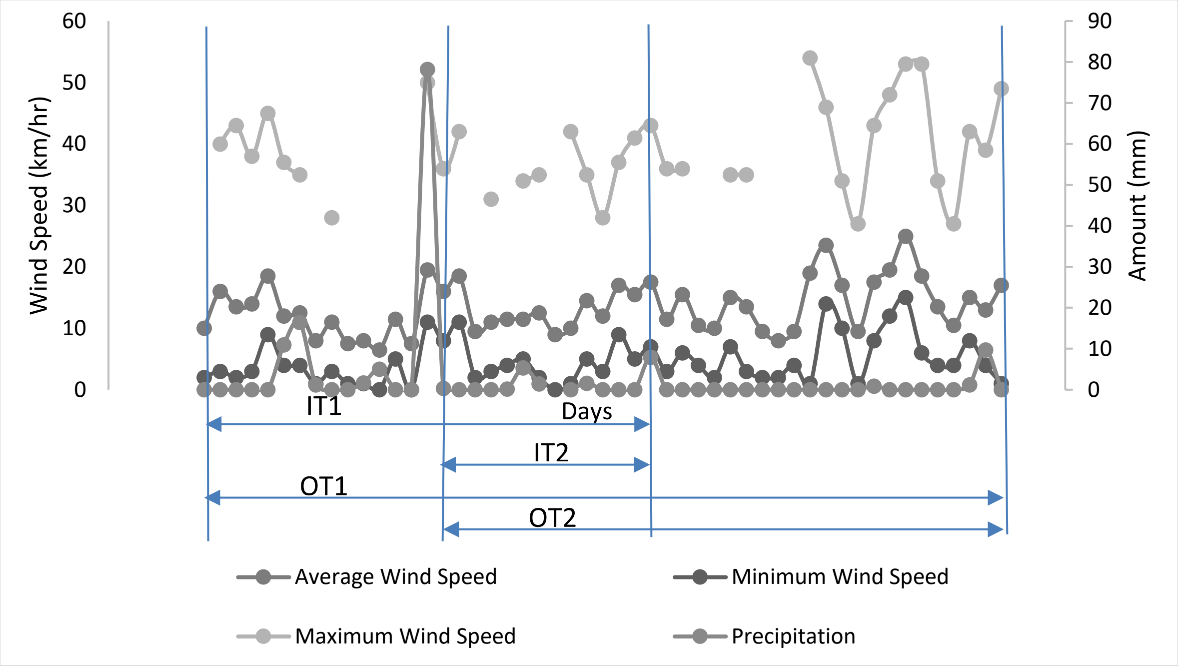

Figure 15 - Antigonish weather data (wind and precipitation) for outdoor trials (compiled from Tracadie, Nova Scotia weather station (Latitude: 45.61, Longitude: -61.68, Elevation: 67 m) via weatherstats.ca.

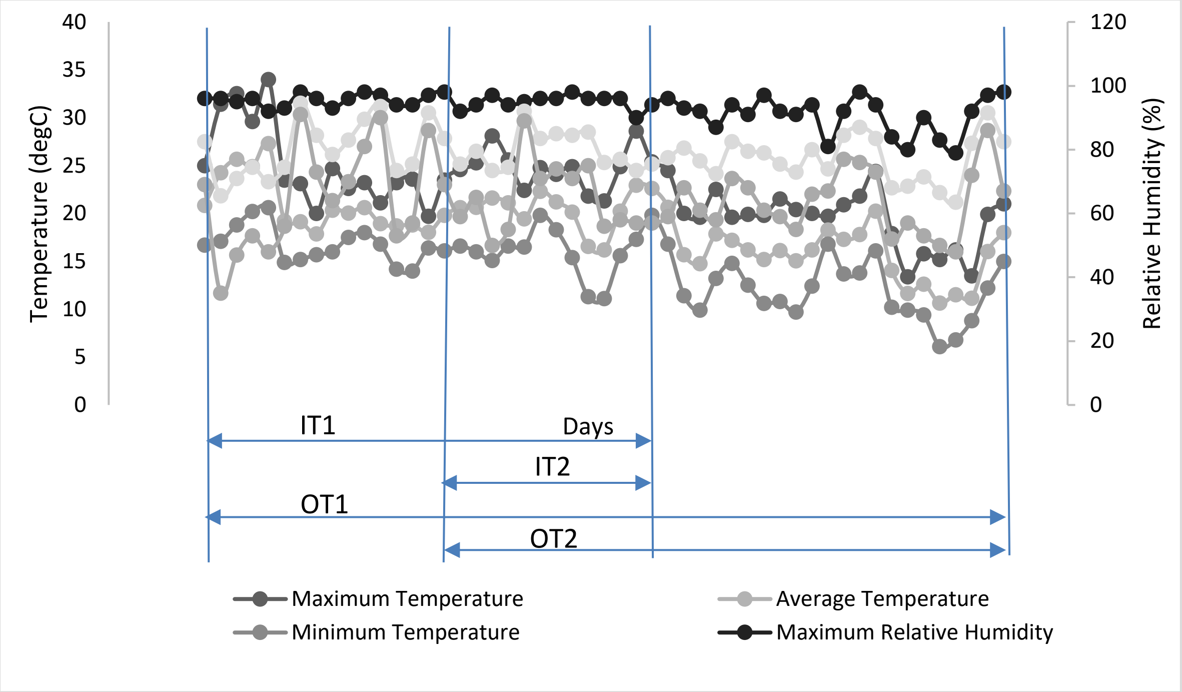

Figure 16 - Antigonish weather data (temperature and humidity) for outdoor trials (compiled from Tracadie, Nova Scotia weather station (Latitude: 45.61, Longitude: -61.68, Elevation: 67 m) via weatherstats.ca

Fig. 17-18 provide weather data for the industry, land-based trials, taking place on a flat laydown area on the case study industry, PHP's site.

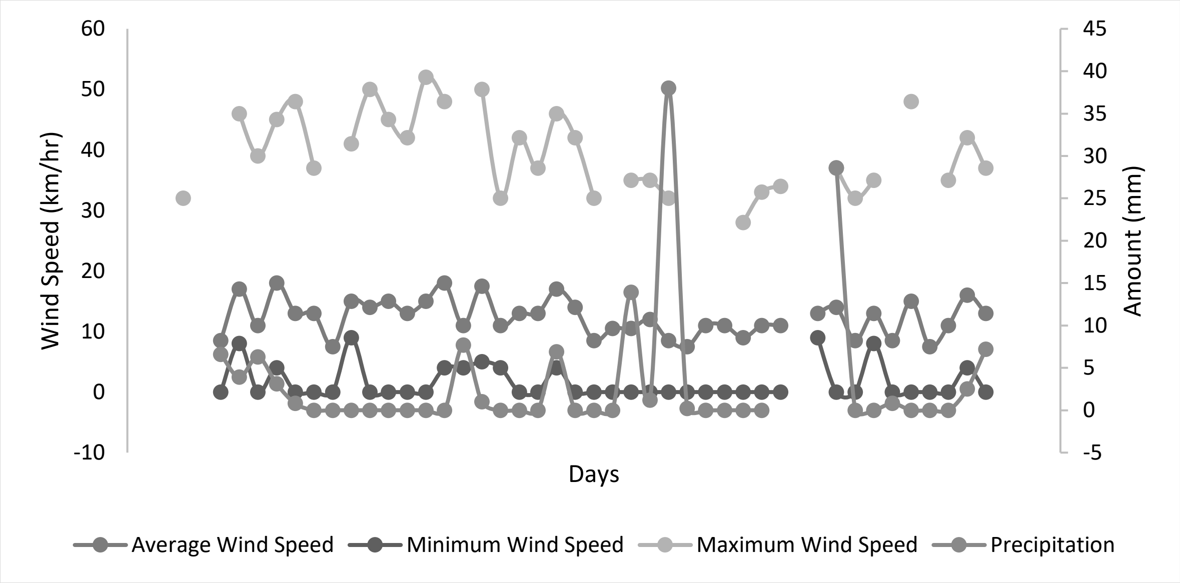

Figure 17 - Port Hawkesbury weather data (wind and precipitation) for outdoor trials (compiled from Port Hawkesbury, Nova Scotia weather station (Latitude: 45.62, Longitude: -61.36) via weatherstats.ca.

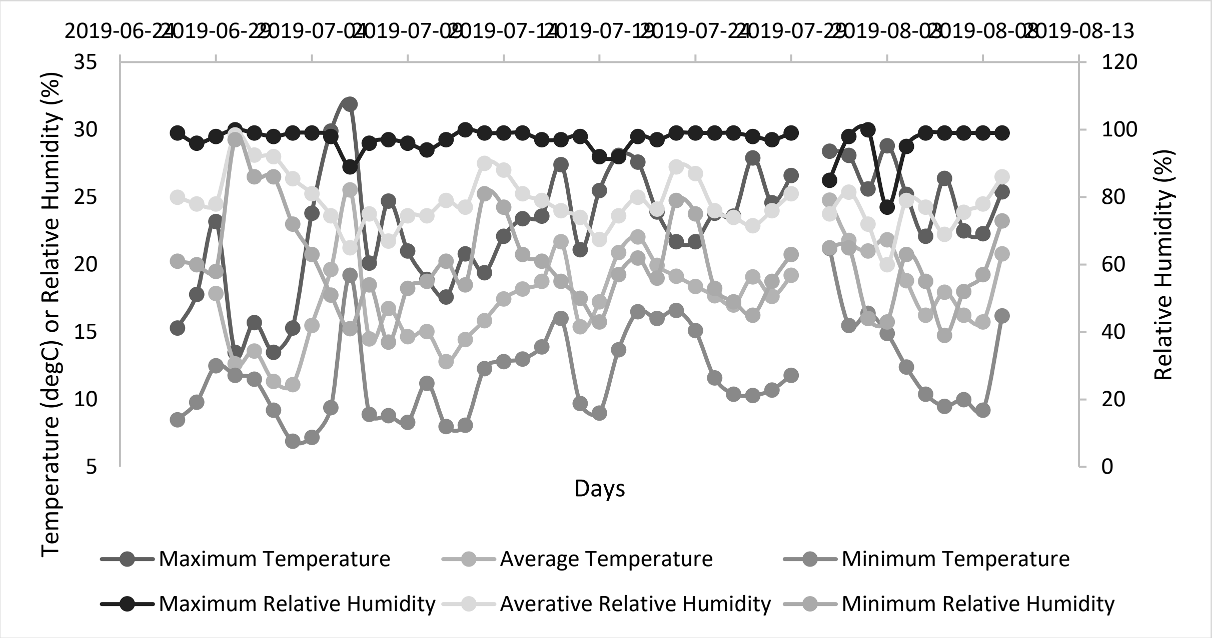

Figure 18 - Port Hawkesbury weather data (temperature and humidity) for outdoor trials (compiled from Port Hawkesbury, Nova Scotia weather station (Latitude: 45.62, Longitude: -61.36) via weatherstats.ca.

CHAPTER 5 POTENTIAL FOR PLANT GROWTH IN PAPER MILL SLUDGE

The article below will be submitted for consideration to the Journal of Material Cycles and Waste Management. Figure and table numbers have been adjusted to fit the flow of this document.

Considerations for paper mill sludge in the capacity of a growing medium

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5.1 Abstract

A waste product from pulp and paper mill is typically sludge, composed largely of cellulosic fibers, clay, and microorganisms. This waste often leaves to landfills and requires a valorization strategy. Pulp and paper mill sludge from a case study industry was tested as a growing medium amendment. Carrots (*Daucus carrota* cv. Nantes Scarlet), lettuce (*Lactuca sativa* cv. Simpson), and strawberries (*Fragaria × ananassa* cv. Charlotte) in greenhouse pot-experiments and Sludge-Promix mixtures with sludge ranged from 0 to 100% by mass were utilized to gauge the ideal sludge application rates through evaluation of plant stress, product quality, transfer factors, and qualitative evaluation. Carrots deformity was absent in growing media with 25% or more sludge while lettuce growth in up to 75% sludge exceeded that of a typical soilless media, with increased leaf greenness observed at three weeks post-transplant. Strawberries were positively affected by sludge integration with soil, with best results found in test cells containing 50% sludge. Chemical indices (pH, conductivity, total dissolved solids, and salinity) maintained $R^2 > 0.5$ with regards to sludge application rate (%). Bioaccumulation factors of key nutrients were < 1 apart from magnesium, sodium, boron, and zinc. Lettuce showed a higher update of magnesium, boron, and zinc, while the carrots showed a significantly higher uptake of sodium by nearly 50%. Overall suggested best application rates are 25% or less sludge inclusion with Promix for carrots and lettuce and 50% or less sludge inclusion for strawberries.

5.2 Highlights

- Pulp and Paper mill sludge has the potential to act as a partial soil replacement
- The pH of paper mill sludge requires adjustment to enhance growth
- Pulp and Paper mill sludge increased the growth rate in strawberry and carrot plants
- A higher volume of strawberries can be grown in 50% sludge than in Promix alone

5.3 Keywords

Soil amendment; waste valorization; pulp and paper mill biomass, sustainability

5.4 Introduction

A common product of pulp and paper mill processes is a biosolids matter aptly called sludge. Sludge varies in composition depending upon pulp and paper plant design. Port Hawkesbury Paper (PHP) located in Port Hawkesbury, Nova Scotia, Canada consists of a thermomechanical (TMP) pulp mill, kaolin clay plant and supercalendered (SC) paper mill with the capacity to produce 400,000 short tons of SC paper (Port Hawkesbury Paper LP, 2022). They produce over 7 tonnes per hour of waste sludge. PHP’s sludge is largely composed of cellulosic material, kaolin clay, and microorganisms. PHP’s sludge is currently stored in an on-site landfill with a portion being burned by a nearby power plant via biomass burning. This is not a sustainable practice, with the need for valorization and a cradle-to-cradle approach. Use of the waste sludge has been an ongoing challenge, largely due to its high moisture content (70%) rendering the biomass burning process inefficient.

PHP has previously evaluated their sludge as a fuel for burning, waste stream for capture of low-grade heat, and a soil amendment. MacDonald *et al.,* (2018) conducted a study on the use of chemicals to reduce the moisture content in pulp and paper mill sludge for optimized burning in a biomass power plant located next to PHP. Although that study found moisture adjustment of the sludge resulted in improved burning capacity, this option does not render the full volume of sludge produced usable and does not provide a high value end use given the low calorific value of the sludge and the high volume of ash post-burn. From onsite investigation the location of all sludge-based outputs at PHP is not ideal or plausible for low-grade heat extraction; the location of processes which could utilize the low-grade heat are at a distance from the extraction point such that transportation would require an additional heating source or insulation which is inefficient for the energy gain available. The use of the waste sludge as a soil amendment was first considered when grass grew remarkably well around PHP's clarifiers and in areas where sludge was stored (such as on the roof of the building which outputs sludge into a pile for pickup). These observations have continued over several years without formal investigation. This sparked the consideration of paper mill sludge in the capacity of a soil amendment or fertilizer. Consideration was given to the end-user, and it was determined that in its natural form there would be both difficulty with regards to the presence of moisture (one would be purchasing more water than dry material), and again, the ease of use.

Additives such as gypsum and fly ash were considered by PHP, however, even when a cement-like ball or pellet were produced the usefulness of the pellet would still have difficulty competing in a domestic market. Other studies have been published that investigated the use of pulp and paper mill sludge for plant growth, with many specifically considering waste from newsprint producing mills, or the use of recycled newsprint. Deinked newsprint waste with a combined stream of sanitary sewer when utilized for corn growth, showed promise of nutrients, but required additional nitrogen (O'Brien *et al*., 2002, Camberato *et al*., 2006, Faubert *et al*., 2016). A similar waste stream without the addition of sanitary sewer is found to show promise with nursery plants, but again noted the need for nitrogen (Chong & Purvis, 2004). Studies conducted using PHP's sludge for energy crops (not for consumption), found that increased yield occurred when using the sludge product (Dalzell, 2021). Most similarly to this research is Abbey *et al.*'s (2021a, 2021b, 2022) studies which considered bioaccumulation and growth potential of lettuce utilizing municipal solid waste compost. The results of that study supported annual application of municipal solid waste compost and found that concerns of toxicity over time in consumables was negligible.

This study develops foundational knowledge for understanding plant growth of three different food crops with different botanical characteristics i.e., a leafy green, root vegetable, and fruit.. PHP's acidic sludge suggests issue for the leafy green in this study as lettuce thrives in slightly acidic soils, in the pH range of 5.5 to 6.5 (Henry *et al*., 2018). Takahashi (2012) found that lettuce germinates best under low pH of 4 at which many root hairs are formed whereas at a slightly higher pH of 6, few roots are formed. Strawberries thrive in a more acidic environment within a pH range of 5.4 to 6.5 (Dixon *et al.,* 2019). Carrots are known to thrive in mildly acidic soils within a pH range of 5.5 to 7 (Delahunt & Newenhouse, 1998). Literature suggests that carrots and strawberries have potential for growth if the pH can be raised, which can be done through mixing with higher pH component, as is being done in this study. Strawberries are susceptible to contamination pre- and post-harvest, often falling victim often causing early decay through lack of nutrients or storage conditions. Sludge is suggested to improve carrot fertility in mixtures of 50% sludge or less (Nahar & Shahadat, 2021). In general pulp and paper mill sludge has shown potential for lowering bulk density of the soil, increasing water retention, and mitigating the effects of erosion (Camberato, 2006).

Nutrient availability from soil or fertilizers plays a crucial role in plant growth and nutrient value of the final harvested produce. The role of nitrogen in plant growth is to support the creation of starches and amino acids, while phosphorous supports cell division and is crucial in the seedling stage of plant growth along with its use in enzymes (NSW Department of Primary Industries, 1970, Dellero, 2020). Together, nitrogen, in the form of nitrate, can increase phosphate response (Kumar *et al.,* 2021).

A gap in literature exists with the consideration of acidified pulp and paper mill sludge for use in specific plant applications along with the comparative effects on numerous plant types, such as fruits and vegetables for consumption. Additionally, the study sludge includes sanitary sewer, creating a modified sludge stream. The purpose of this study was to identify the potential use of pulp and paper sludge as soil amendment for plants, consider heavy metal bioaccumulation, and determine if the presence of sanitary sewer is detrimental to this end use. This study is critical to the industries strides toward sustainability.

5.5 Materials and Methods

5.5.1 Study Location and Material

Experiments took place in a southwest facing greenhouse atmosphere at the Dalhousie University Agricultural Campus (Truro, Nova Scotia, 45.3716° N, 63.2641° W). Trials took place from May to September 2022. Pulp and paper mill sludge was provided by Port Hawkesbury Paper LP (Port Hawkesbury, Nova Scotia, Canada). Carrot (Carrots, *Daucus carrota* cv. Nantes Scarlet) and lettuce (*Lactuca sativa* cv. Simpson*)* seeds were purchased from Feeds’n Needs (Truro and Antigonish, Nova Scotia, Canada). Strawberry (*Fragaria* × *ananassa* cv. Charlotte) were purchased from a nursery, Gray's Greenhouse (Addington Forks, Nova Scotia, Canada).

5.5.2 Experimental Design

Three plant species were used in this study: (1) a root vegetable (Carrots, Daucus carrota cv. Nantes Scarlet*),* (2) a leafy green (Simpson Lettuce), and (3) a fruit, (an everbearing strawberry, Charlotte cv. *Fragaria* × *ananassa*). Experiments on each species were independent.

The lettuce seeds were germinated in Promix BX (Halifax Seed, Halifax, Nova Scotia, Canada) under 80 W lights 24/7 for four weeks and then transplanted test cells (plastic plant pots) containing varied amounts of sludge and Promix. The lettuce trials took place over approximately 8- and 10-weeks post-transplant. The carrot seeds were germinated in the study mixtures, and the strawberries were transplanted from their seedling state in a soilless media into mixtures of this media combined with various percentages of sludge. In the transplanting process, ideally one will choose seedlings of similar size, to allow for comparability. In the case of the first trial, this was not possible due to strawberry seedling availability from a third-party supplier. To reduce inconsistency, randomization of larger seedlings occurs throughout the replicates. Strawberry seedlings were chosen for this study based upon consistency in appearance, with chosen transplants ideally being without flowers.

Two duplicate trials were undertaken for the lettuce and one for the carrots and strawberries. Three replicates were taken per trial, of each sample mixture.

Carrots were grown within a greenhouse environment with daily watering and no additional treatments. All were planted and randomized (replicates were not side-by-side) in the greenhouse environment. Approximately ten seeds were planted in each pot with the goal of germination of at least five seeds per pot. Seeds were planted sporadically throughout the pot, ensuring ample space for root development, the seed depth was approximately 1 inch below the free surface. Harvested carrots were examined for deformities (additional limbs, shape, color, etc.) and then separation of roots and stalks occurred. The carrot trial took place over approximately 10 weeks.

Strawberry seedlings were grown in the test soil pods in an external greenhouse/ nursery. As with lettuce, seedlings of similar size, absent of flowers, were chosen wherever possible and randomization was used in planting. The strawberry trial took place over approximately 9 weeks post-transplant.

Throughout all trials, consistent, daily watering took place, providing each pot/ plant with approximately 0.4 L of water.

The plants considered in this experiment did not undergo any form of additional treatment.

Fresh pulp and paper mill sludge collected from PHP in the spring and summer of 2022 was used in the experiments. This sludge was characterized as having a pH of approximately 4.7 and 30% consistency (70% moisture content). On a dry weight basis, the sludge has an approximate C:N ratio 2241.9, total organic and inorganic carbon respectively represent 42.7 and 3.9% respectively (Dalzell, 2021). A typical N:P:K value is 4:1:1 but varies. The sludge was mixed on a mass percent basis with Promix as outlined in Table 8:

The mixtures considered are as follows with a mixture containing only soil as a control/ baseline:

Table 8 - Actual masses of sludge (wet basis, 70% moisture content) and Promix used for carrot (*Daucus carrota*), lettuce (*Lactuca sativa*), and strawberry (*Fragaria* × *ananassa*) growth trials. Values are represented in text as Sludge-Promix (S-P) (with percentage relating to sludge by mass).

Mass Sludge (%)	Mass Promix (%)	Carrot		Lettuce		Strawberry	
		Mass Sludge (g)	Mass Promix (g)	Mass Sludge (g)	Mass Promix (g)	Mass Sludge (g)	Mass Promix (g)
100	0	1328	0	400	0	1000	0
90	10	1195.2	132.8	360	40	900	100
75	25	996	332	300	100	750	250
50	50	664	664	200	200	500	500
25	75	332	996	100	300	250	750
10	90	132.8	1195.2	40	360	100	900
5	95	66.4	1261.6	20	380	50	950
0	100	0	1328	0	400	0	100

The Promix BX contains various helpful additives such as perlite (Silber *et al.,* 2010).

5.5.3 Environmental Conditions

Environmental conditions for sludge sampling align with work conducted by MacDonald-MacAulay *et al.* (Chapter 4.11) regarding grass growth. Specific trial growth conditions are presented in Appendix 5A.

5.5.4 Data Collection Methods

Chlorophyll fluorescence indices (plant stress via Fv/Fm) was determined using a handheld Chlorophyll Fluorometer (OS30p+ by Opti-Sciences, Hudson, New Hampshire, United States) and chlorophyll content (greenness) was measured using a Chlorophyll Meter (SPAD 502 Plus, by Spectrum Technologies, Aurora, Illinois, United States). These measurements were taken on both the strawberry and lettuce plants. Carrots were not included in these measurements as they are root vegetables and stems were too thin to extract data using these technologies. Two leaves on each plant were tested to determine stress and chlorophyll values in plants, optimally, not consecutive leaves. Strawberry firmness was measured using a Fruit Firmness Penetrometer (GY-03 by Jacksking, Amazon). An EC 500 ExStik II S/N 252957 multimeter (EXTECH, Nashua, New Hampshire, United States) was used to record pH, salinity, total dissolved solids (TDS) and electric conductivity (EC) of the test soils. These tests took place at the beginning of the study. Soil (growth media) samples were diluted in distilled water at a ratio of 1:2, mixed thoroughly, and left to sit for 24 hours before measurements occurred. All plants received approximately 0.4 L of water per day and were organized in a randomized fashion to mitigate uneven conditions.

Through harvesting of the lettuce, dead leaves were removed, and a fresh weight was taken. Once complete, the leaves were dried for 3 days at 65ºC and weighed, with the difference determining the moisture present.

Strawberry harvest occurred as each berry matured. Physical harvest occurred when the berries were fully red and exhibited some sponginess upon the application of mild pressure, similar to what one would seek prior to consumption.

Yield measurements for carrots and lettuce required weights of dry and fresh samples.

5.5.5 Nutrient, Microbial, and Chemical Analysis

Tissue analysis was conducted utilizing a Standard Plant Tissue Package to determine N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Na. These tests were conducted at the Department of Agriculture Lab in Bible Hill, Nova Scotia, Canada. Carrot roots and lettuce leaves were collected in full available masses, and post-drying were placed in Ziploc bags and frozen.

Complete metals (via EPA3050B, Acid Digestion of Sediments, Sludges, and Soils (US EPA, 1996)) and e-coli analysis were conducted through RPC Laboratories in Fredericton, New

Brunswick as well as through METH2013 based on EPA6020 by Maxxam Laboratories (now AGAT) in Sydney, Nova Scotia.

Nitrate as N were tested by AGAT (Dartmouth, Nova Scotia, Canada) Laboratories via ion chromatography (INORG-121-6005, SM 4110 B) focusing on liquid waste stream outputs from the case study industry.

Bioaccumulation Factor was determined through division of the concentration of nutrients present in the consumable portion of the plant by the concentration of nutrients available in the growth amendment mixture (S-P).

5.5.6 Statistical Analysis

Microsoft Excel V2302 was utilized to construct graphs while XLSTAT 2023 facilitated two sample t-test analyses comparing measured sample outcomes and base mixture compositions, principal critical analyses, and one way Analysis of Variance (ANOVA) testing. These tests focused on fixed factors of base mixture composition (ex. 25% sludge, 75% Promix). These analyses focused on the determination of statistically significant connections between base mixture composition and various measured quantities such as root length.

5.6 Results and Discussion

5.6.1 Soilless media- Sludge Characteristics

Characteristics of the growing media mixtures used in this study are presented in Figure 19. pH data from Figure 19 indicates a trend in decreasing pH with an increased presence of sludge and a statistically significant connection ($p < 0.05$). An ideal pH for plant growth of the chosen plants used in this study is between 5 and 6. The sludge on its own is often at a pH of less than 5 from PHP’s real-time readings, excluding it from candidacy as a sole growth media. The low pH is attributed to the acidification portion of the study industry’s dewatering process through addition of 93% sulfuric acid.

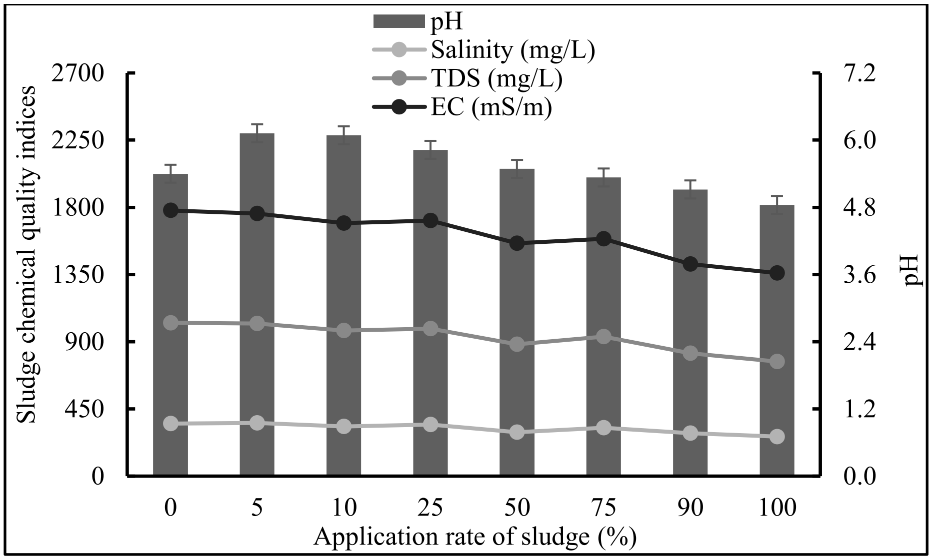

Figure 19 - Chemical quality indices of varying proportions of sludge and Promix soilless mixed media. TDS is total dissolved solids; EC is electric conductivity. The vertical bars represent standard error bars (N = 4).

Conductivity measurements in Figure 19 remained between 600 and 700 mS/m with a trend of decreasing conductivity with increasing sludge percentage. The conductivity does not follow a linear pattern with a decrease until 25% S-P and then another decrease beyond the inclusion of 50% sludge. Conductivity in plant growth depends upon the presence of nutrients, organic materials, clay, etc. (Hawkins *et al.,* 2017; Andrea, 2022). Low values of conductivity compared to the ideal range are often indicators of a need for nutrients, while a high value can be indicative of an overabundance of nutrients. For soils specifically, the ideal range is typically between 100-400 mS/m (Andrea, 2022); comparing with the values in Figure 19, the soils used in this research have high conductivities compared to the range presented by Andrea (2022), potentially linked to the porosity of the soils (USDA Natural Resources Conservation Service, 2011). Overall, all conductivity measurements in this study including the control 100% soil mixture are within a similar range ($p < 0.05$).

The salinity of mixtures remained relatively consistent through increasing sludge percentage with a statistically significant connection ($p < 0.05$). The concentration of salt found within soil can typically develop from weathering of rocks and degradation through other processes. The salt becomes prominent at the root level due to the evaporation of water, leaving salt behind in high, potentially damaging concentrations depending upon characteristics of the area and soil (Corwin & Yemoto, 2020, Bhatti *et al.,* 2021). While the salinity is largely consistent, outside of the 10-25% range of sludge inclusion, the salt present in the mixture would indicate, even at the highest outliers, that all mixtures are deemed non-saline being below 3 g/l (< 3000 ppm) based upon Brouwer *et al.* (1985) or within acceptable range based on Abbey *et al.*'s (2022) work). In areas of high soil salinity, damage can be caused at the root level, obstructing intake of water and nutrients (Corwin & Yemoto, 2019). Measurement through EC, as determined with an aqueous solution is an indirect form of measurement of salinity (Corwin & Yemoto, 2020). The outcomes from Figure 19 relieve the concern that, in any concentration, the presence of sludge would increase salinity.

The total dissolved solids (TDS) yield a direct relationship with salinity of soil ($p < 0.05$), with mass of TDS aiding in defining potential for high salinity. While already considering the negligible concern of high salinity in all mixtures, the TDS values are shown to largely decrease with increasing presence of paper mill sludge ($p < 0.05$), further reducing the concern.

Table 9 shows strong correlations between chemical quality indices and percentage of sludge included in the growth media, where values in bold represent significant p-values. R^2 values indicate closeness to linear regression with all values above 0.5, and electrical conductivity showing the greatest potential to follow linear behavior.

Table 9 - Analysis of Variance (ANOVA) statistics for chemical quality indices of varying proportions of sludge and Promix soilless mixed media.

	Source	DF	Mean squares	F	P-value	R^2
pH	Model	1	0.995	13.192	**0.011**	0.68736
	Error	6	0.075			
	Corrected Total	7				
Salinity	Model	1	6218.360	21.218	**0.004**	0.77956
	Error	6	293.067			
	Corrected Total	7				
Total Dissolved Solids	Model	1	23818.519	43.794	**0.001**	0.8795
	Error	6	543.874			
	Corrected Total	7				
Electrical Conductivity	Model	1	25664.349	146.271	**<0.0001**	0.9606
	Error	6	175.458			
	Corrected Total	7				

5.6.2 Carrot Growth Trials

Figure 20 displays the number of germinated carrot seeds across the trial. One-week post-plant sprouts were seen in the 100% soil sample. By week 3 carrot germination 5 and 10% S-P showed capacity for competing with growth in soil alone due to the number of seeds germinated (Figure 22). Once surpassing 50% S-P, germination dramatically decreases to a near zero value. The results of this study demonstrated that application greater than 50% S-P was detrimental to carrot seed germination. The high conductivity of the sludge in this study could link to the wilting of carrots in high sludge percentages due to an excess of available nutrients. The test cells with 10 to 50% S-P sludge mixed with soil showed comparable seed germination results that found in the control test cell (0% S-P). There is a significant correlation ($p < 0.05$) for each trial compared to application of sludge and germination, but there is not a statistically significant correlation between the two trials.

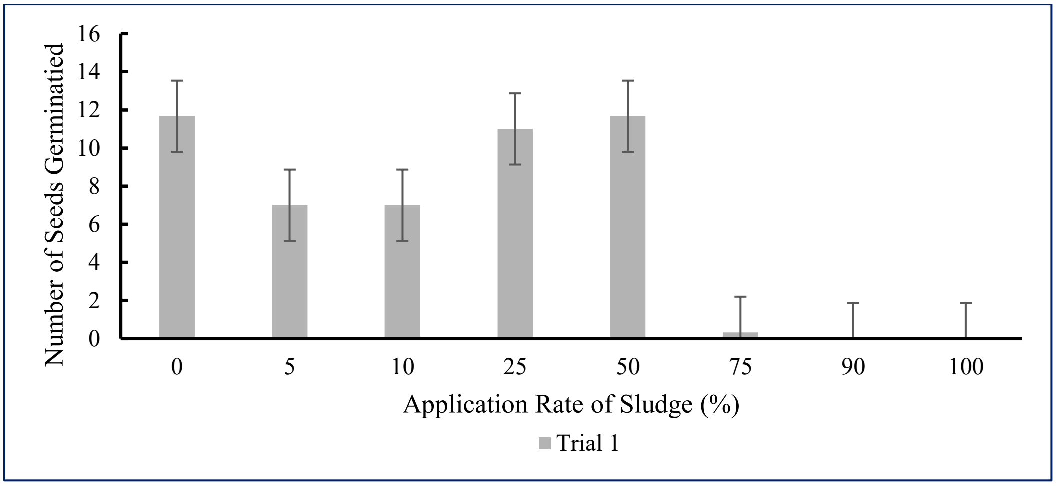

Figure 20 - Average germination numbers for carrot (*Daucus carrota*) trial out of 10 possible seeds grown in varying proportions of sludge and Promix soilless mixed media. The vertical bars represent standard error bars (N = 2).

On average, mixtures containing sludge provided carrots with minimal to no deformities, whereas the 0% S-P mixture provided appropriately shaped carrots, but in 2 out of 3 replicates, deformities were recorded (Figure 21). This supports the potential for slow-release fertilizer behavior (Chapter 4). Like the grass trials from MacDonald-MacAulay's work where the grass originally germinated quickest in low concentrations of sludge, but as time passed, higher concentrations passed and exceeded growth in low concentrations and in 0% S-P.

Figure 21 - Harvested carrot (*Daucus carrota*) roots from carrot trial 1 grown in varying proportions of sludge and Promix soilless mixed media.

Stem lengths were measured throughout the trials and are shown in Figure 22 with broken stems removed from data, and it was found that stem growth was non-existent with the inclusion of greater than 50% S-P, however, low-mid percentages of sludge produce similar lengths of stems.

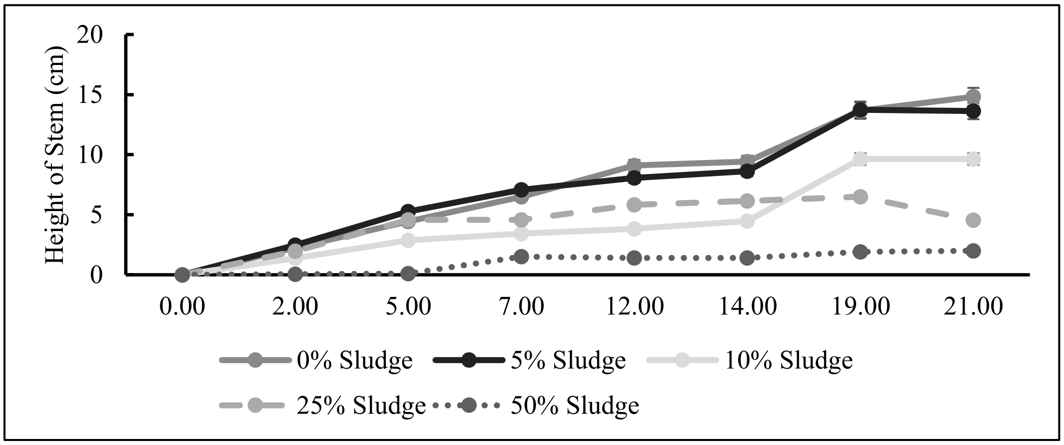

Figure 22 - Heights of carrot (*Daucus carrota*) stems vs. days post plant grown in varying proportions of sludge and Promix soilless mixed media ($p > 0.05$). The vertical bars represent percentage error.

Figure 23 reflects the fresh and dry masses of harvested carrot roots and stems. Fresh root masses were similar from 0-25% S-P, however, 5% S-P samples slightly exceeded all others. Dry values were consistent across samples. This would suggest that 5-10% S-P is optimal for carrot growth.

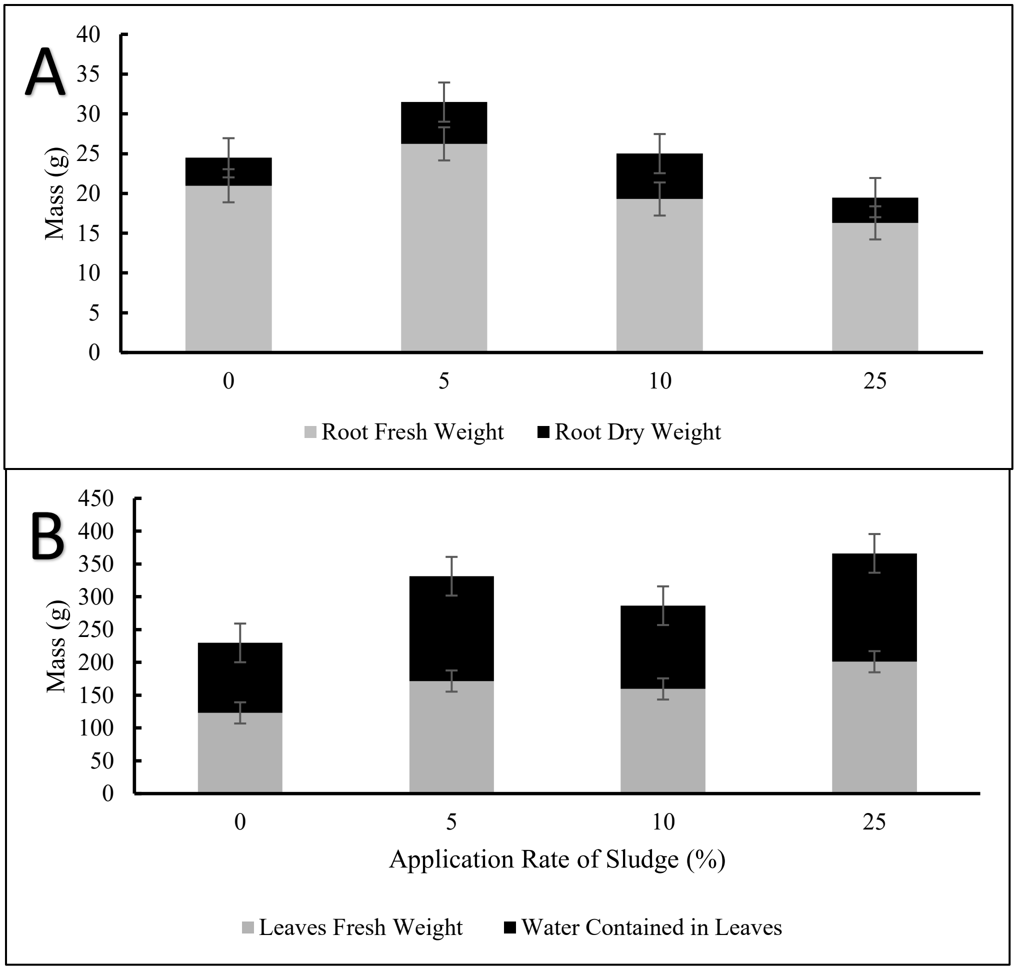

Figure 23 - Carrot trial (*Daucus carrota)* harvested root (A) ($p < 0.05$) and leaf (B) ($p > 0.05$) masses grown in varying proportions of sludge and Promix soilless mixed media. Vertical bars represent error percentage.

Figure 24 displays the length and width of carrot roots grown in various percentages of sludge. Samples containing 5-10% S-P produce competitive sized roots to that of 0% S-P samples. The p-values indicate significant positive connections between the composition of the growth media (sludge percentage) and size characteristics of roots produced.

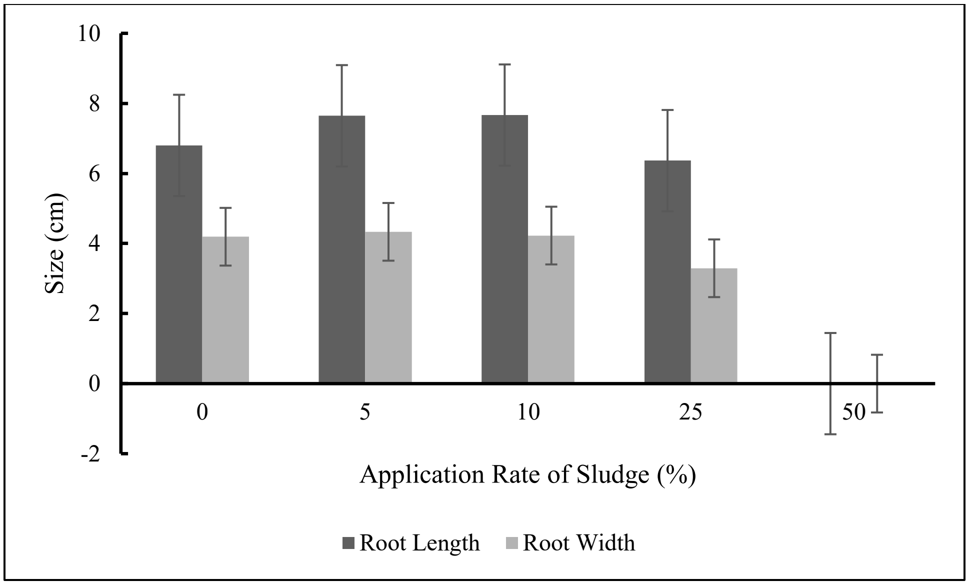

Figure 24 - Carrot trial (*Daucus carrota*) length ($p < 0.05$) and width ($p < 0.05$) of roots harvested grown in varying proportions of sludge and Promix soilless mixed media. The vertical bars represent percentage error.

5.6.3 Lettuce Growth

The average mass of lettuce harvested in relation to the different growing media are presented in Figure 25. The results showed that greater than 50% S-P of the soil with sludge resulted in a decrease in the mass of lettuce produced. The rapid decline in lettuce plant growth observed is likely facilitated by increased presence of aluminum found in sludge along with sludge's low pH. When combined with soilless media (Promix), the pH of the system is raised above 5 which allows for better growth and mitigates the effects of the aluminum. However, phytotoxicity occurred and while some seedlings began to grow in the sludge, albeit not at a rate to contend with those in the soilless media. The germinated seeds did not flourish beyond minimal exposure above the free surface. Literature has suggested that the presence of aluminum, combined with a low pH can be detrimental to plant growth (Takahashi, 2012).

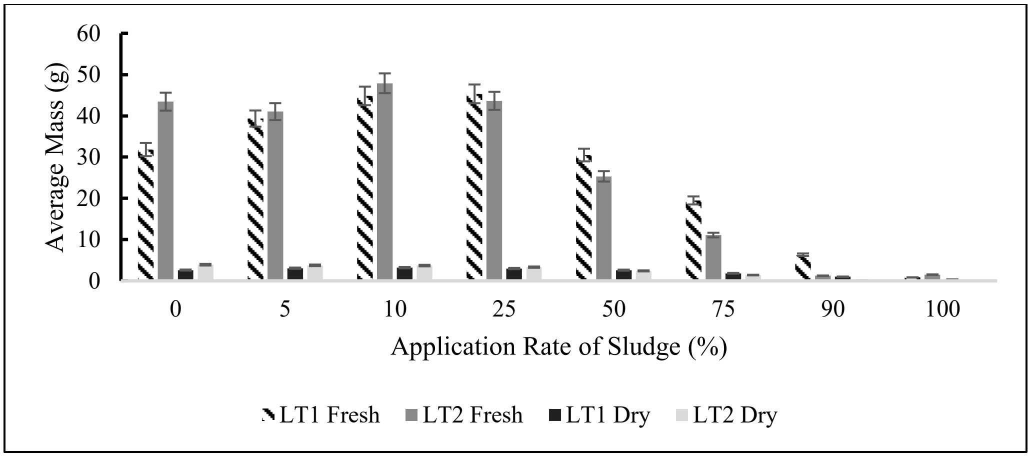

Figure 25 - Lettuce (*Lactuca sativa*) trial data indicating mass of harvested material grown in varying proportions of sludge and Promix soilless mixed media. ($p < 0.05$). Vertical bars represent percentage error.

Figure 26 provides leaf counts for LT1; an increase in the number of leaves grown is seen in up to 50% S-P.

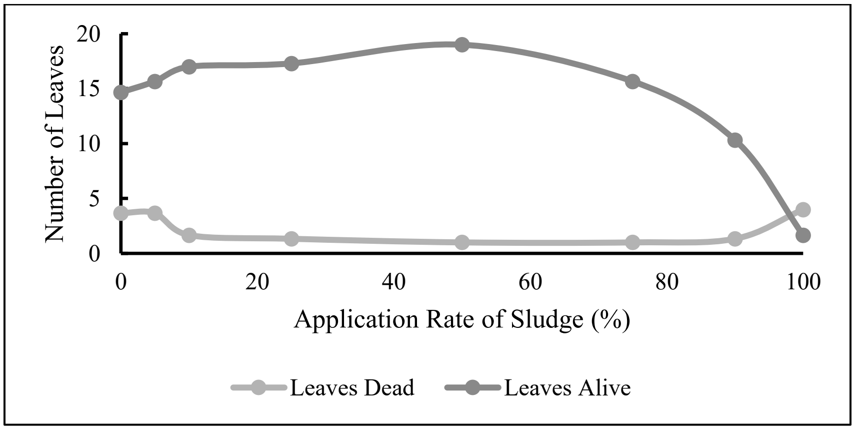

Figure 26 - Leaf number counts on harvested heads of lettuce (*Lactuca sativa*) in varying proportions of sludge and Promix soilless mixed media ($p \sim 0.05$ or less).

Figure 27 suggests that at 3 weeks post plant, lettuce grown in 50% S-P exceeds the greenness rating of all other samples while 25% S-P mixtures exceed leaf length in other mixtures (Figure 28).

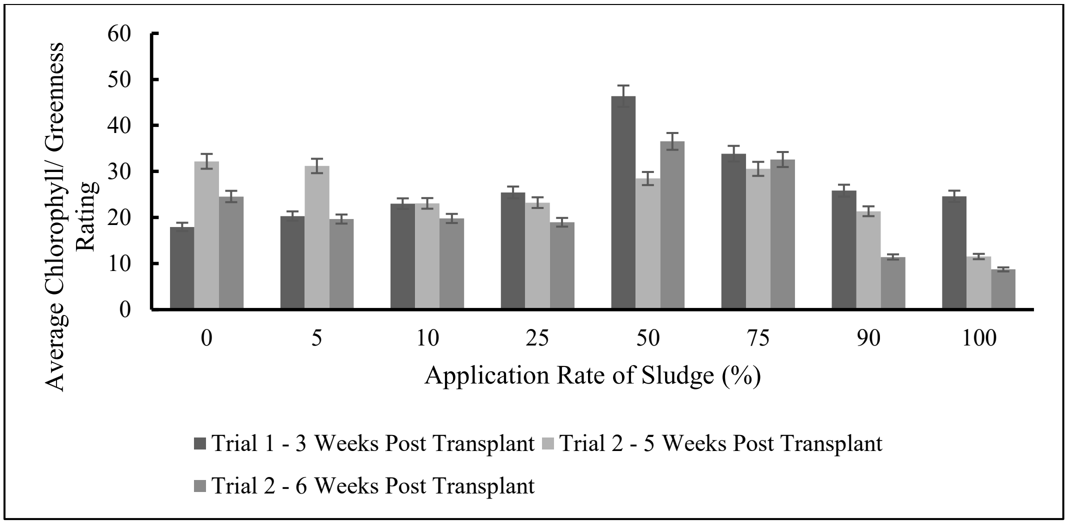

Figure 27 - Lettuce (*Lactuca sativa*) trial 1 chlorophyll ratings 4 weeks post plant in varying proportions of sludge and Promix soilless mixed media ($p > 0.05$). Error bars indicated in percentage.

Figure 28 displays leaf lengths averaged through the lettuce trial with plants grown in various percentages of sludge. The positive correlation between sludge percentage and leaf length is statistically significant.

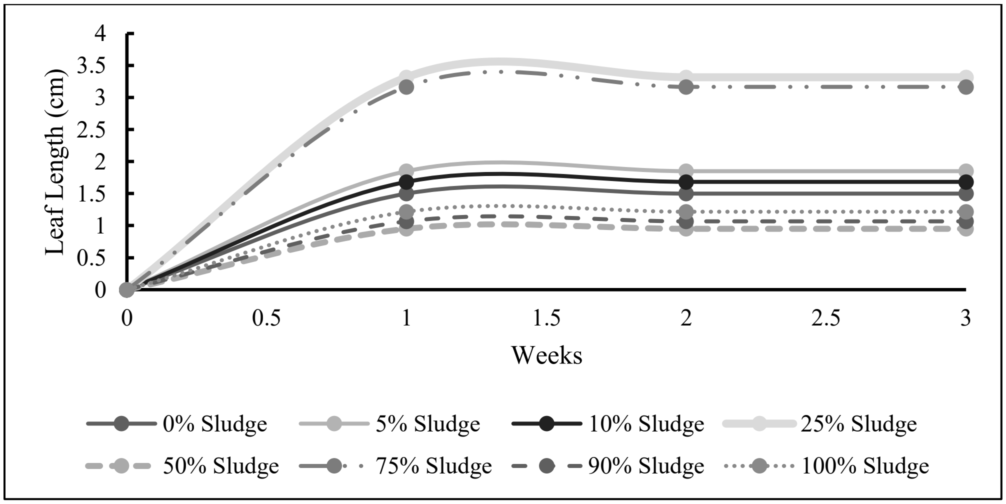

Figure 28 - Lettuce (*Lactuca sativa*) trial 2 - Average leaf lengths throughout trial in varying proportions of sludge and Promix soilless mixed media ($p < 0.05$). Sampling began 3 weeks post plant. Error bars indicated in percentage.

5.6.4 Strawberry Growth Trials

Chlorophyll fluorescence readings beginning 4 weeks post-transplant from the strawberry plants are presented in Figure 29. In test pods containing more than 50% S-P samples were seen to wilt 5 weeks following transplant. The strawberry plants grown in 0% S-P were shown to have the lowest chlorophyll fluorescence measurements indicating the highest stress compared to the other plants in this study. The presence of sludge in the test growth media resulted in increased chlorophyll fluorescence values indicating an environment more conducive to growth. Additionally, post fruit production values increase on average, with increasing sludge presence up to 25% S-P, further supporting the potential for SRF behaviour (MacDonald-MacAulay *et al.*, 2023).

Chlorophyll fluorescence measurements indicate whether light is utilized in plant leaves to promote photosynthesis, or dissipation of heat energy or emission as light (Maxwell & Johnson, 2000). Flourishing plants are typically supported through a chlorophyll fluorescence reading of approximately 0.83; a lower value indicates the plant experiencing higher stresses (Maxwell & Johnson, 2000).

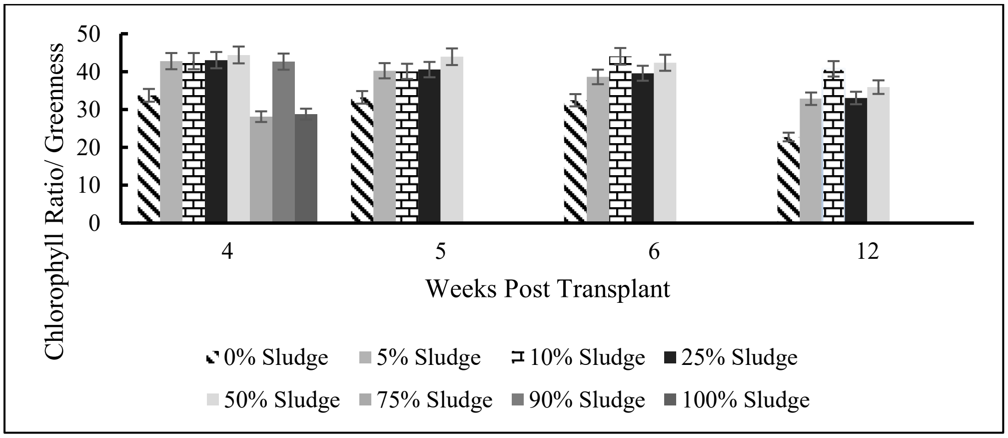

Figure 29 - Strawberry (*Fragaria* × *ananassa*) chlorophyll ratings 4 weeks post plant in varying proportions of sludge and Promix soilless mixed media ($p > 0.05$). Error bars indicated in percentage.

The strawberries notably thrived with a small presence of sludge. Figure 30 displays stress readings for strawberry plants grown in various percentages of sludge. As shown in Figure 30 the strawberries exhibited high stress values (lower magnitude Fv/Fm) post fruit production (of the first plant at approximately 55 days post-transplant). The presence of sludge is shown in all times of measurement to be beneficial to reduction of stress. 5 and 25% sludge mixtures have shown to be the most favorable. Plants grown in 90 and 100% S-P showed high stress values linked to an overabundance of nutrients.

The stress experienced by the strawberry plants was shown to be negligibly affected in the presence of sludge. Literature suggests that tannin and lignin lead to the dark coloration of paper mill sludge, increasing light and heat intake (Bhatti *et al.*, 2021). The p-value at 36 days is statistically significant ($p < 0.05$). The p-value beyond 36 days is above 0.05, proving insignificant.

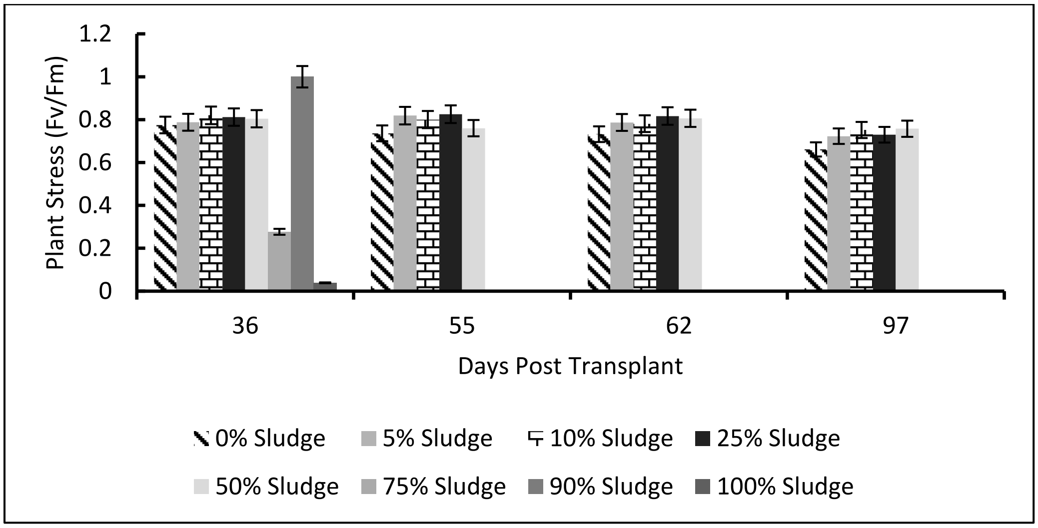

Figure 30 - Plant stress experienced by strawberries (*Fragaria* × *ananassa*) over the duration of the trial in varying proportions of sludge and Promix soilless mixed media.

Data in Table 10 shows the number of berries produced and their relative hardness values versus the percentage of sludge in the growth media. Table 5 indicates that the 50% sludge mixture produced the greatest number of strawberries for harvest. Notably, the plant grown in 5% S-P showed the first berry growth. Beyond this point no strawberries were produced. Interestingly, at 0% S-P, no strawberries grew to harvest size, the young green berries were present, but did not grow beyond this stage. A significant statistical relationship between sludge percentage and number of strawberries and hardness values is not found.

Table 10 - Number of strawberries (*Fragaria* × *ananassa*) harvested under varied presence of sludge along with average hardness values of strawberries.

Percentage Sludge (mass %)	Number of Berries Produced	Average Hardness (kg/cm^2)
5	2	0.21
25	6	1.08
50	15	0.60

Relevant ANOVA analysis of samples in Table 10 is presented in Table 11. While p-values are insignificant, the linear regression value for hardness closely aligns with that of linear behaviour when compared to percentage of sludge inclusion.

Table 11 - Analysis of Variance (ANOVA) statistics for characteristics of strawberries (*Fragaria* × *ananassa*) grown in varying proportions of sludge and Promix soilless mixed media.

	Source	DF	Mean squares	F	P-Value	R^2
Number of Berries	Model	1	86.568	41.255	0.098	0.152
	Error	1	2.098			
	Corrected Total	2				
Hardness	Model	1	0.058	0.179	0.745	0.976
	Error	1	0.322			
	Corrected Total	2				

The fresh weight of each berry is individually presented in Figure 31, where for example, the greatest volume of berries was produced in 50% S-P. Weights of all berries did not differ significantly across various percentages of sludge.

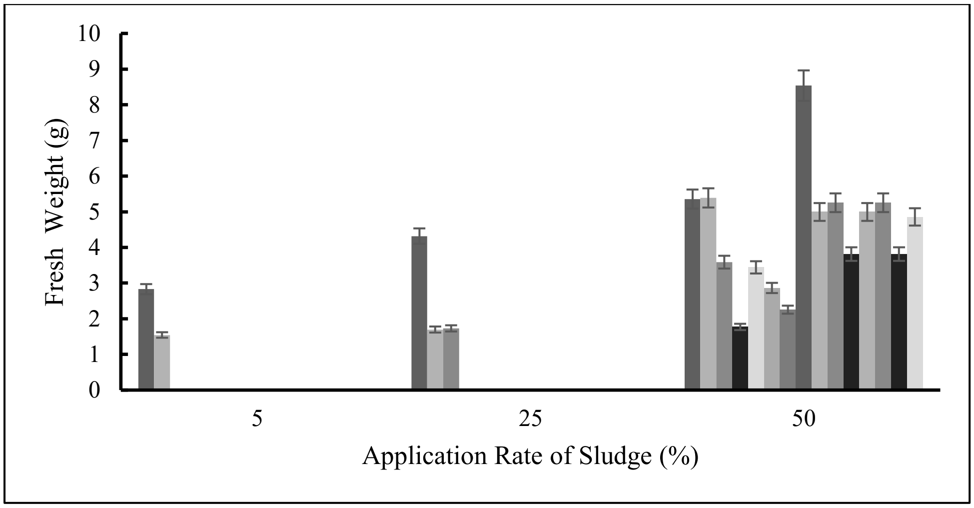

Figure 31 - Fresh mass of strawberries (*Fragaria* × *ananassa*) grown in varying proportions of sludge and Promix soilless mixed media post-harvest.

5.6.5 Bioaccumulation and Nutrient Analysis

Carrots and lettuce grown in media containing 25% sludge had the highest nutrient contents compared to the other treatments (Table 12). Optimal nutrient availability of nitrogen, phosphorous, and potassium are seen in 10 to 25% S-P mixtures. The perceived increase growth rate (size of leaves and greenness in lettuce) seen at approximately 3 weeks with increasing sludge percentage indicates concern for an increased uptake of nitrogen. Vegetative plants such as lettuce are glutinous consumers of nitrogen which can cause adverse health effects when consumed by humans (Brkić *et al.,* 2017). An example of detrimental effects would be Blue Baby Syndrome or Cancer (Salehzadeh *et al.,* 2020). This prompted the need further nitrogen breakdown, specifically concerning the nitrates within the tissue. A 2017 data set from PHP was consulted regarding water testing from several their output streams, including their sludge product. Analyte concentrations were shown to be less than 0.5 mg/L for nitrates, which is below the 10 mg/L limit imposed by the Government of Canada (2014). 5% of the maximum concentration suggests that even with an increase in nitrogen linked to nitrates, the concentrations should remain below safe limits. Additionally, in cases where sludge has been studied in the capacity of a growing amendment, supplemental nitrogen is commonly required or suggested (Turner & Oliver, 2022). The nitrate as N concentration in Promix is 70 – 130 mg/L which is less than the overall nitrate as N concentration in water samples taken with PHP's sludge, being <0.5 mg/L.

Table 12 - Nutrient presence in carrot roots (*Daucus carrota*) and lettuce leaves (*Lactuca sativa*) through tissue analysis of samples grown in varying proportions of sludge and Promix soilless mixed media post-harvest.

	Carrots			Lettuce		
Sludge Present (%)	0	10	25	0	25	75
Nitrogen (%)	0.95	1.33	1.72	2.09	5.19	6.42
Calcium (%)	0.37	0.37	0.33	1.03	0.82	0.40
Potassium (%)	1.70	2.05	1.31	4.26	2.66	1.41
Magnesium (%)	0.17	0.17	0.19	0.30	0.38	0.21
Phosphorus (%)	0.36	0.48	0.60	0.56	0.82	0.71
Sodium (%)	0.53	0.64	1.03	0.48	0.571	0.571
Boron (ppm)	13.27	12.62	16.89	19.09	24.45	-
Copper (ppm)	16.71	5.05	-	-	-	-
Iron (ppm)	41.93	31.79	30.01	53.4	107.18	70.64
Manganese (ppm)	15.67	39.52	45.65	168.66	194.96	152.56
Zinc (ppm)	44.58	65.97	50.06	47.74	78.33	48.92

Bioaccumulation factors for carrot trials are found in Table 13. Manganese increases with the addition of sludge, while iron decreases by almost 40% from Table 12 which could require supplemental iron. High iron and manganese values are positive, supporting 25% sludge as an optimal base mixture, from both Table 12 and 13. Sodium, however, increases with the addition of sludge, but only by 20%.

Table 13 - Bioaccumulation factors for nutrients in carrot (*Daucus carrota*) and lettuce (*Lactuca sativa*) samples.

Plant	Calcium	Potassium	Magnesium	Sodium	Boron	Iron	Manganese	Zinc
Carrot	0.18	9.84	0.82	13.35	1.87	0.03	0.10	1.32
Lettuce	0.45	19.98	1.64	7.41	2.70	0.1	0.45	2.06

5.6.6 Multivariate Analysis

A principal component analysis was conducted to correlate various datasets to determine commonalities between active variables as loadings or base growth mixture composition and active observations varying (Figures 32-34). Figure 32 shows the close relationship between root length, fresh and dry weights, root width, and stem height postharvest in the carrot trials. The leftmost quadrants prove that once more than 50% sludge is utilized in the growth media, growth trends are no longer consistent. Germination and growth media pH are found in the same quadrant, showing the close relationship between these two factors.

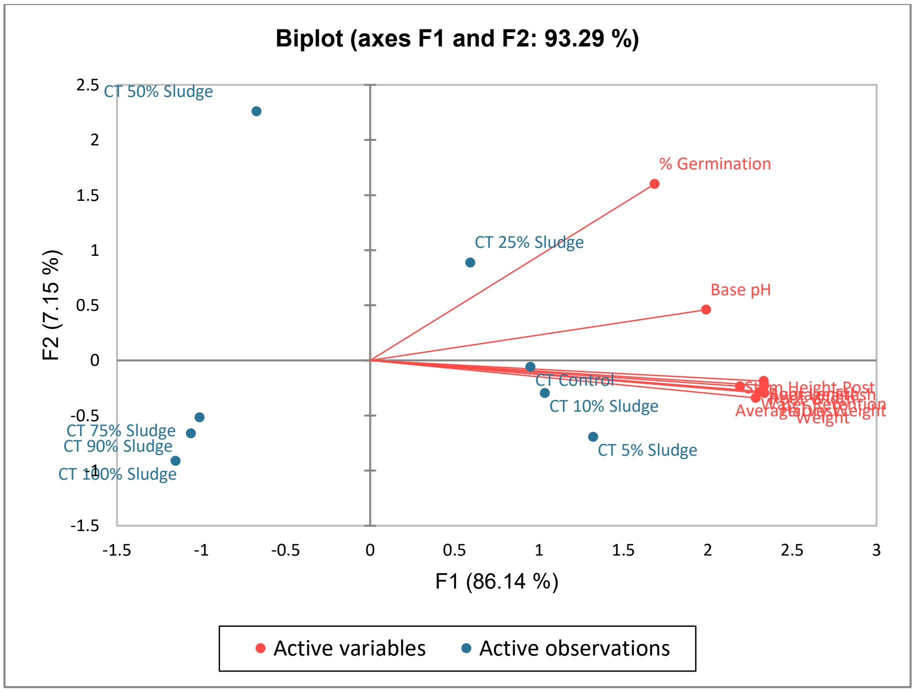

Figure 32 - Multivariate biplot assessing connections between characteristics in carrot (*Daucus carrota*) analyses.

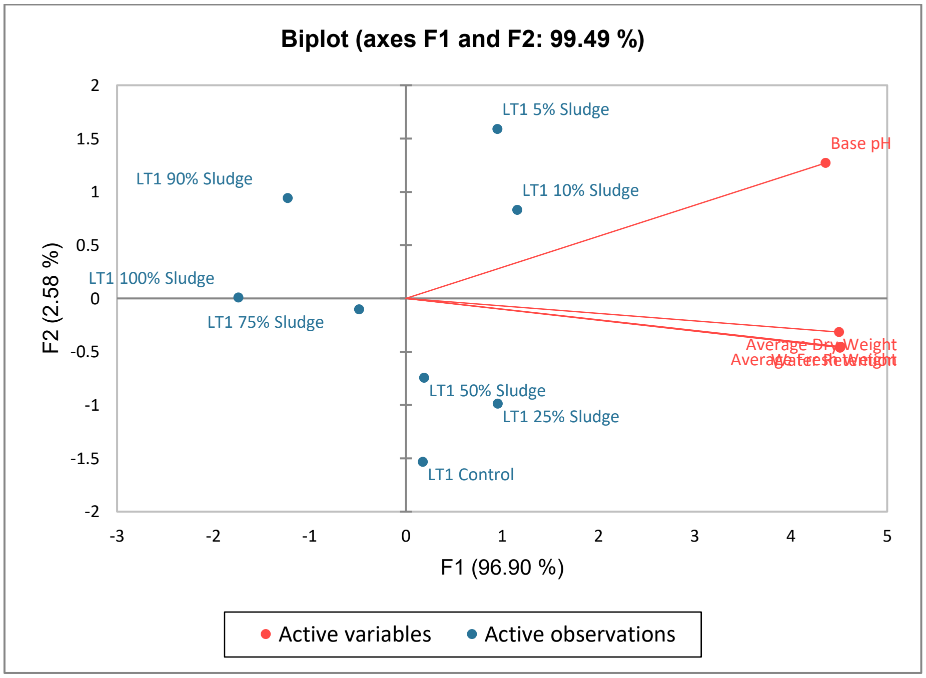

Figure 33 - Multivariate biplot assessing connections between characteristics in lettuce (*Lactuca sativa*) analyses.

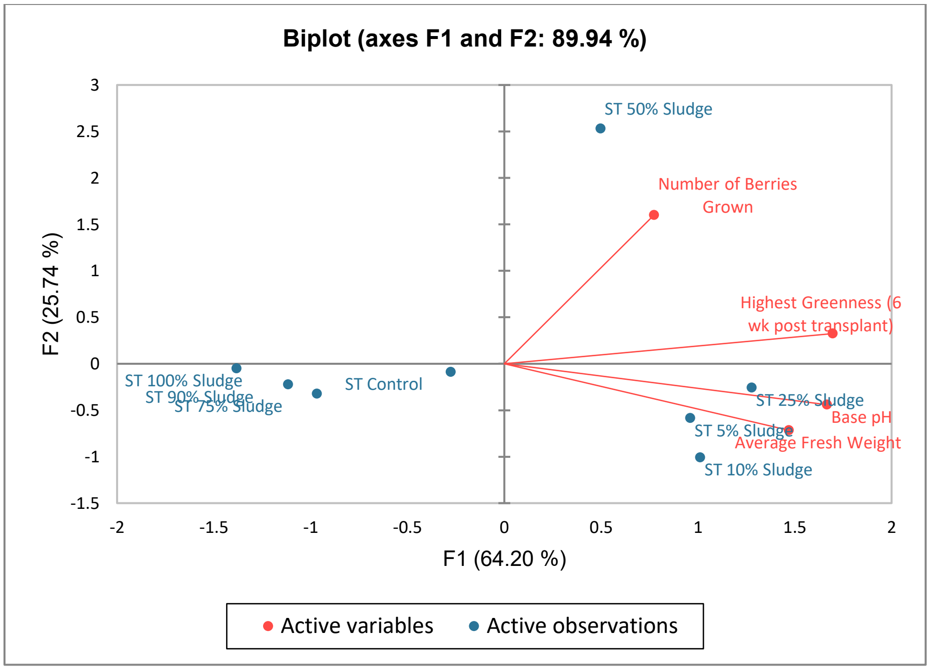

Figure 34 - Multivariate biplot assessing connections between characteristics in strawberry (*Fragaria* × *ananassa*) analyses.

Figure 33 indicates that lettuce growth characteristics of fresh and dry weights have little relation to growth media pH. Figure 34 for the strawberry growth trials shows similarities between growth media pH and fresh weight, and between leaf greenness and the number of berries produced.

Considering Figures 32-34, beyond 50% sludge inclusion in carrots and 75% sludge inclusion in lettuce and strawberries a significant trend was not seen between growth characteristics and percentage sludge addition. This can be seen in the figures where beyond the 50 and 70% sludge points, characteristics fall in separate quadrants from the mixtures. The control mixture shows strong connections with growth characteristics in carrot trials but does not show alignment in lettuce or strawberry trials.

5.7 Conclusions

Overall study goals included determining if pulp and paper mill sludge has the capacity to act as a soil amendment for plant production. 100% sludge would be an unlikely candidate for a soil replacement but does hold benefits when used in combination with a nutrient rich high pH soil such as Promix. The three plant types chosen were adversely affected by being placed in 100% sludge mixtures. Moving forward, it is suggested that no more than 50% sludge with Promix be used on a case-by-case basis. Carrots were grown successfully without deformities in up to 25% sludge-Promix mixture, while lettuce grown in up to 75% sludge exceeded that of a typical soilless media. Strawberries were positively affected by sludge integration with Promix, with the best results found in test cells containing 50% sludge. Initially it was clear the 100% sludge mixtures were detrimental to plant growth, with failure to germinate or maintain plant health.

5.8 Acknowledgements

Thank you to Gray's Greenhouse (Addington Forks, Nova Scotia) for being a consistent supplier of plants, but also for their knowledge in discussion on the related work. Port Hawkesbury Paper is acknowledged as long-term research supporting and funding source. We would also like to recognize the support from a Mitacs Accelerate Grant – IT32158 - Paper mill biosolids reuse through integration into hydroseed mixtures.

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5.10 Appendix 5A Environmental Conditions

Water intake through roots can be negatively affected by low temperatures, indicating that the trials undertaken in this study occurred in optimal conditions, during the spring and summer months (Ni *et al.,* 2019). General abiotic condition data is presented in Figure 35.

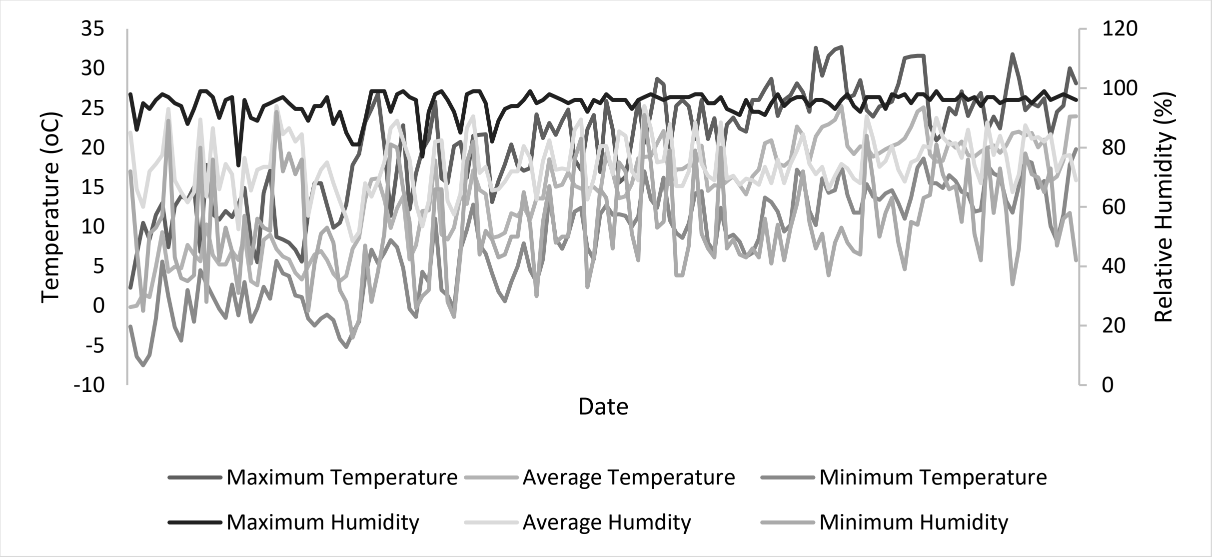

Figure 35 - Weather conditions over duration of all greenhouse-based trials. Data based on Truro, Nova Scotia (Latitude: 45.37 and Longitude: -63.28).

CHAPTER 6 CONCLUSION

Paper mill sludge has the capacity to replace the cellulosic component typically found within hydroseeding mixtures. Comparatively, both are largely composed of cellulose (paper), however, paper mill sludge combines this with the presence of nutrients unavailable in ripped newspaper.

For use as a tacking agent, on an incline, sludge mixtures did show reduced movement when water was applied.

While water retention of the cellulosic comparative (Celumulch) exhibited greater water retention by mass than sludge, the density of sludge resulted in a 15-fold reduction in required volume for equivalent water retention. This indicates that sludge for transport and purchasing purposes would be the best option, due to a lesser volume being required. Conversely, the sludge in its current state would likely require local pickup due to its high moisture content whereas Celumulch is easily transported in its dry state.

The use of sludge for the growth of strawberries (*Fragaria × ananassa*), carrots (*Daucus carrota*), and lettuce (*Lactuca sativa*) did not prove more beneficial than a typical soil or fertilizer; however, there is potential for its use in plant growth. In the case of lettuce, the addition of sludge was detrimental to growth over the typical time to maturity. Lettuce did however mature quickly in sludge, with the potential for early harvest. With carrots, roots grown in low percentages of sludge were found to be comparable, if not longer and with a larger diameter than those grown in soil. The earliest strawberry growth was seen in mixtures containing small percentages of sludge; however, overall growth upon harvest did not prove better than a typical soil mixture.

Upon review of the initial research questions:

1) “Does paper mill sludge have the potential to be used as a soil amendment?

   Response: Recognizing the need to potentially mitigate negative impacts of low pH for some plants (such as lettuce), paper mill sludge has the potential for use as a soil amendment. Sludge as an amendment material appears especially suited for plants that thrive in slightly acidic environments, potentially increasing germination rates while yielding comparable final products post-harvest.

2) Is paper mill sludge a better additive for hydroseeding purposes than the typical cellulosic component?

Response: Paper mill sludge is competitive with the typical cellulosic component used in hydroseeding and increases the rate of germination. Mid-low percentages of sludge produce the quickest, densest growth, while high percentages of sludge produce the longest blades. 100% sludge can be utilized for hydroseeding but is not optimal. The indoor and outdoor environments differed in germination by approximately 1 week.

   a. Is growth period reduced with sludge?

Response: The ideal percentage of sludge for quickest germination of grass seed for hydroseeding application is 5-25% sludge to soil.

   b. What is the ideal application rate and composition of a sludge-hydroseed mixture?

Response: The ideal application rate is a total mix of soil, sludge and seed at 525 g/ft^2 with 5-75% sludge for densest growth. For overall growth, 5-75% sludge provides the best coverage beyond three weeks post application.

3) Does paper mill sludge have the capacity to replace the need for a tacking agent in hydroseed applications.

Response: The need for tacking agents has the potential to be replaced by paper mill sludge.

Visual observations in the small-scale trials indicated sustained growth nearing the tops samples on inclines. Optimal stability is achieved in all mixtures (including 100% sludge) 1 month post plant. On a 3:1 slope, growth outcomes competed with, and exceeded those in Celumulch.

4) What pre-treatments are needed to create a ‘usable’ mixture for land application, if any?”

Response: While pre-treatment was initially suggested due to high concentrations of heavy metals (such as Selenium or Nickel), the application rate and dilution upon application removes the concern of uptake of metals. Through testing of soil media (mixed with sludge) and grass samples metals were well below regulatory levels.

Considering the individual plant growth trials of carrots, lettuce, and strawberries, complete replacement of soil and/or soilless media is not suggested. A mixed media approach consisting of 25% sludge-Promix or less for carrots and lettuce and 50% sludge-Promix or less for strawberries is suggested. The work with these plants has mitigated the concern for bioaccumulation or transfer of heavy metals and/or bacteria. However, monitoring would need to take place long term should this process be implemented.

Revisiting eco-industrial park potential, the opportunity to utilize PHP’s sludge without additional treatment presents an optimal opportunity for a partnership. If the inclusion of sanitary sewer presents a concern to potential customers or partners, it can be separated from the process sewer line. Payback considerations are uniquely positive as relief of this waste material not only removes PHPs current transport costs but could also create an income stream. Any interested parties considering this work, including the case study industry, should undertake similar trials over a longer duration of time, which will also facilitate regulatory needs such as satisfying the Fertilizers Act. Considering environmental and health effects the scope of additional research should be broadened to include leachate testing, changes in soil nutrient level, and proximity to water sources. It would also be beneficial for nutrient and organic component measurements to be collected seasonally to create a range of nutrient values.

Future work involves the need to identify the potential to utilize weathered sludge in the capacity of plant growth and hydroseeding. Testing of weathered sludge would involve determination of decomposition of materials over time, as well as differences between layers due to years of process changes and additions of material such as gypsum from nearby industry sites.

Additionally, direct testing against known tackifiers could take place in comparison to sludge use. A variety of soil types should also be considered. Relatedly, a full life cycle assessment should be undertaken, specifically to determine greenhouse gas related outcomes.

Blueberries are known to flourish in acidic environments like that of strawberries. This would be an ideal future experiment as fruits may prove to be a potential consumable market with the use of pulp and paper mill sludge as a growth media. Relatedly, with all food crops, investigation into combinations of soil or varied soil types would be beneficial; for example, one may consider where sandy soil is an issue, sludge could be added in a loam-like combination to strengthen the soil.

Finally, the work with plant growth has shown pH to be of concern, which can easily be remedied through the addition of a basic agent such as lime (Hale *et al.,* 2020). Opportunities exist to further supplement and create value with PHP’s sludge or similar waste streams.

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APPENDIX A Initial Project Charter Calculations Toward Sludge Sale Opportunities

Project Name: Increased Residual Value through Sanitary Sewer Diversion (Preliminary Investigation)

Department: Engineering

Product/Process: Divert Sanitary Sewer Stream

PROJECT OVERVIEW

PHP produces a valuable bio-solids product (sludge) which at this time is being investigated for use in various commercial capacities. The cellulosic composition of PHP'ssludge has already proven useful for burning operations in its current state but could move beyond on-site use.

Cape Breton has seen wood pellet shortages over the last number of years which in many cases requires outsourcing to manage the needs of local users. PHP could contribute to thislocal market and beyond through the production of pellets from a mixture of sludge and various combination residuals (bark, sawdust, Tim Hortons cups, willow, etc.). Canadian Tire for example sells a 40lb bag of hardwood pellets (we would have softwood which increases value) for ~$6.00.

Sludge could also become part of a soil amendment, combining with gypsum (availablelocally as well) and again, bark, willow, etc. Canadian Tire sells for example, sheep manure as a soil additive in 12.5 kg bags at a price of ~$3.00.

Sanitary sewer is present in PHP's final sludge product in small amounts; however, thiscan be an issue to potential users outside of the industrial setting, not only for public perception, but also for meeting environmental standards.

PHP will also be experiencing a likely increase in sludge removal costs in the next yeardue to changes in landfill agreements. Costs are currently estimated at ~$70,000/yr in trucking costs, again with an expected increase in the future.

With potential removal of trucking costs due to production of a salable product it isexpected that potential savings/income could extend well beyond the trucking costs(calculations found below).

It is estimated that due to the likely need for a 'middleman' to distribute pellets to a largerseller as well as freight charges, etc. PHP would likely sell pellet bags for ~$3.00 / 40lb

200t/day sludge x 2240lb/t = 448,000lb/d

448000lb/d x 250 working days/yr = 112,000,000lb/yr
112000000lb/yr/40lb/bag =

2,800,000 bags/yr2800000bags/yr

x $3.00/bag= $8,400,000/yr

*if reduced as low as 3t/d output (minimum) income would be ~$126,000/yr.

The calculations above are of course based upon a comparative sale value to a Canadian seller and would likely be less than such during initial stages and this assumes that all sludge would be sold. Likely a portion would continue to be utilized by NSP or for PHP'sinternal use.

Comparatively, with the soil amendment, utilizing a reduced (by $1) value from the sheep manure example, and then halved for freight, below again shows valuable savings.

112000000lb/yr x (1kg/2.204lb) =

50,816,697kg/yr

50816697kg/yr/12.5kg/bag =

4,065,336 bags/yr 4878402bags/yr x

$1.00/bag = $4,065,336/yr

*if reduced as low as 3t/d output (minimum), income would be ~$60,980/yr

The overall project/ use could involve creating both pellets for burning and for a soilamendment depending on local needs, economics, etc.

Looking now further to costs of production, assuming two operators at ~$50,000/yr, cost of machinery to transport sludge/ pellets around mill depending upon final location of operation assumed at ~$100,000, cost of a bagging machine, bags and equipment (loader) bags ~$500,000-1,000,000. This would reduce profit by at least $100,000/yr for workers and provide a payback period of far less than 1 yr (if utilizing pellets at ~200t/d). However, depending upon the infrastructure required, partnerships with bagging industries, etc. this could change.

***Please now refer to the following, practical example utilizing the pelletizingcalculations and assuming the use of 10t/d.*

10t/day sludge x 2240lb/t = 22,400lb/d

22400lb/d x 250 working days/yr =

5,600,000lb/yr

5600000lb/yr/40lb/bag = 140,000

bags/yr 140,000bags/yr x $3.00/bag=

$420,000/yr

The above example would then represent a likely payback period of less than 3 years.

It is, at this time the goal to price a treatment system for separation of sanitary sewer from our current stream. The sanitary sewer line connects to the process at a singular point andcould be diverted with little effort.

GOALS & OBJECTIVES

Goals	**Objectives**
- Separate sanitary sewer from process streams - Produce value-added sludge - Obtain quoted price for diversion system	1. Work with engineering company to understand potential costs of diversion of sanitary sewer (new treatment, etc.) 2. Produce sludge for use without presence of fecal coliforms

APPENDIX B Land Trials – Additional Information and Photos

Following up on the long-term observation that sludge, when placed on land, has the potential to grow grass, preliminary tests took place with the assistance of professional hydroseeding company. Preliminary testing revealed the potential for successful growth; the mixtures were sprayed on their respective areas with attempts at minimal overlay. The application area is largely level. The laydown area prior to hydroseeding is seen in Figure 36.

Figure 36 - Initial 15 x 7' laydown area for hydroseed trials. The left side represents the use of Celumulch and the right side represents the use of sludge.

The procedure demonstrated in Figure 37 is consistent with a typical hydroseeding application.

Figure 37 - Cannon style spraying technique to cover large areas and avoid clogging of larger particles. Spray contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

The laydown area immediately post application is seen in Figure 38.

Figure 38 - Panoramic view of laydown area immediately following hydroseed application. Left-hand side represents typical hydroseed mixture and right-hand side represents sludge based hydroseed mixture. Sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

The laydown area approximately 12 days following the hydroseeding application is seen in Figure 39. The rectangle represents a small amount of growth appearing in the corner of the sludge side of the laydown area.

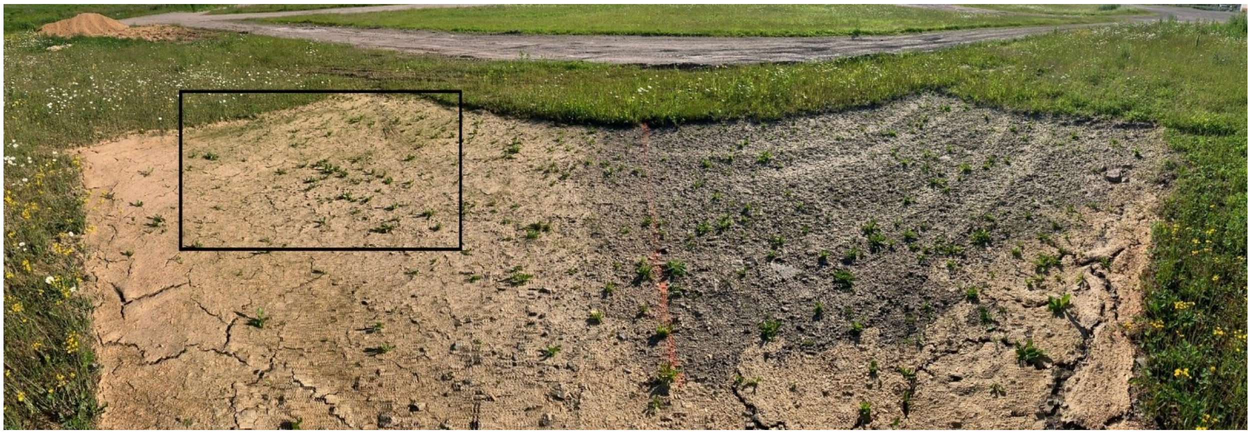


Figure 39 - Panoramic view of 15 x 7 ft area with orange line dividing sludge side (left) and Celumulch side (right) after 12 days. Sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Figure 40 provides a closer view of the grass blades appearing on both sides of the laydown area. The upper portion displays a higher growth density indicating that the presence of sludge appears to be visibly beneficial compared to Celumulch.

Figure 40 - Close up view of hydroseed area, top representing sludge side and bottom representing typical hydroseed side. Samples contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Following the proof of concept and potential the 6 x 6" squares were placed on each site with visible changes. Grass follicle counts are presented in Table 14, coupled with a visual representation in Figure 41.

Figure 41 - Final measurement of grass follicles within squares on day 25, left representing sludge side and right representing typical hydroseed side. Sides contained grass growth

composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Table 14 - Grass follicle count for 6x6" area in hydroseeding tests. Sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Day	Number of Grass Follicles in Celumulch Side	Number of Grass Follicles in Sludge Side
12	9	43
15	12	47
18	22	57
20	24	62
25	34	80+

Imprecision Uncertainties *u* (Number of Grass Follicles) = ±5
*All comparisons differ.

Figure 42 provides linear function estimations for both hydroseed mixtures, showing the sludge side with a much higher y-intercept and slightly greater slope. The data is consistent with the visual observations. From a qualitative perspective, the exhibited speed of growth and density of coverage well exceeds that of a typical hydroseeding mixture.

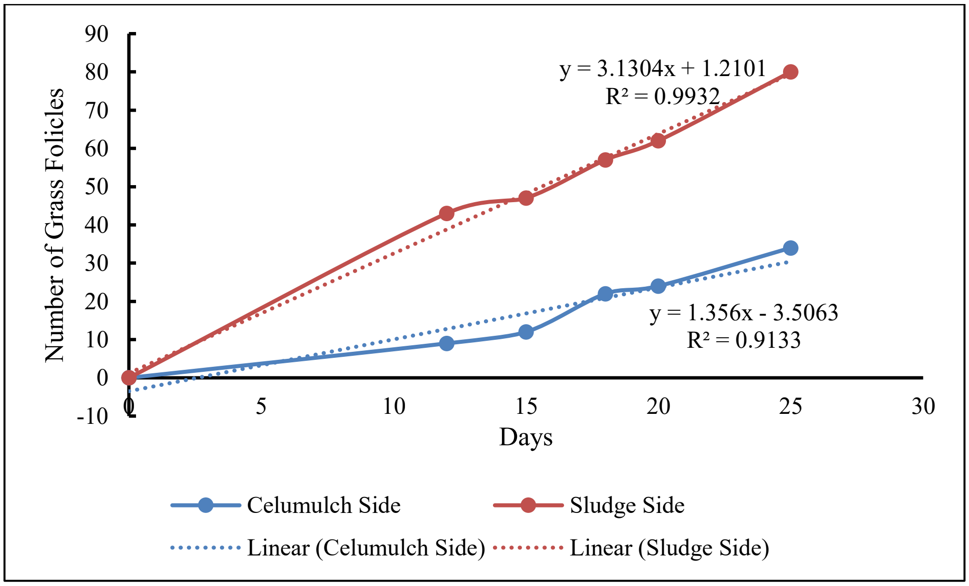


Figure 42 - Growth tracking for recycled paper-based hydroseed mixture versus paper mill sludge-based hydroseed mixture.

This data provides proof of concept that sludge based hydroseed mixtures show a higher and faster rate of growth within the first month. This is likely due to the presence of nutrients common in fertilizers, nitrogen (N) and phosphorous (P) in the following ratio, BOD (Biological Oxygen Demand):N:P – 100:4:1. Also, notably both sides of the test area do not include a tacking agent which is typically present in a hydroseed mixture to help with adherence to the ground (Haynes, 1997). For the trial, no maintenance occurred, and the samples were in an exposed area which underwent numerous days of wind, heavy rain, and sun. The sludge side visually presented a greater amount of the seed material remaining after heavy rains, and while a layer of sludge remained present, when removed, the grass was not growing from the sludge, but from the ground beneath, removing the risk of the grass potentially being lost in layers.

Additional testing has occurred utilizing paper mill sludge; O'Brien *et al.,* 2002 tested paper mill sludge and soil mixtures with regards to corn growth. The findings of this study showed that paper mill sludge provided additional organic content and phosphorous but did not provide sufficient nitrogen, even when supplemented with additional nitrogen. These findings are further supported by Chong & Purvis (2004) where nursey grown plants were shown to flourish in the composted (turned in an outdoor environment over a number of months until odors subsided).

A sample (10-15 g) of grass was tested with the resulting metals concentrations being well below all CCME; pertinent results are found in Table 15.

Table 15 - Comparative results from grass follicle metals testing on sludge based hydroseeding patch against CCME Soil Quality Guidelines for protection of human and environmental health (Source: Canadian Council of Ministers of the Environment, 2019)

		Soil Quality Guidelines - Concentration (mg/kg dry weight)			
Metal	**Concentration (mg/kg dry weight)**	**Agricultural**	**Residential**	**Commercial**	**Industrial**
Antimony	<2	20	20	40	40
Arsenic	<2	12	12	12	12
Barium	10	750	500	2000	2000
Beryllium	<2	4	4	8	8
Boron	<2	2	N/A	N/A	N/A
Cadmium	<0.3	1.4	10	22	22
Chromium	<2	65	64	87	87
Cobalt	<1	40	50	300	300
Copper	2	63	63	91	91
Lead	<0.4	70	140	260	600

Blades of grass grown in 100% and a 25% sludge– 75% soil mixture, along with the base growth mixtures were tested for metals and nutrient accumulation and/or availability, with results found in Table 16.

Table 16 - Nutrients & Metal Concentrations in 100% sludge and a 25% - 75% sludge – soil mixture containing seed with 40% Creeping Red Fescue (Festuca rubra), 30% Perennial Ryegrass (Lolium perenne), and 30% Kentucky Bluegrass (Poa pratensis).

Nutrient	Amount present in 100% Sludge (mg/kg)	25% Sludge – 75% Soil (mg/kg)
Nitrogen	1,700	-
Calcium	1,850	18,200
Potassium	380	1,330
Magnesium	330	2,330
Phosphorous	1,000	-
Sodium	1,330	770
Boron	15	9
Copper	5	28
Iron	320	1,100
Manganese	1,030	438
Zinc	12	38

APPENDIX C Bench-Scale Trials – Additional Information and Photos

The following trials are based upon the initial success of the outdoor land trials. The considerations consider questions from stakeholders as well as comparisons and methodologies from literature.

Outdoor Trial 1

The initial outdoor trials visually indicated that the quickest, densest growth occurred in mixtures containing 10-25% sludge, when considered approximately 5 days after planting. After the full trial, the longest growth (blade length) was exhibited in the highest sludge percentages, but the densest growth remaining in the low-mid percentages of sludge. Notably, this competes with the Celumulch mixture typically used in hydroseeding applications. Water retention was observed to be higher in the Celumulch and 90-100% sludge mixtures. Considering the retention, the outcome at this point was expected, given that the cellulosic component is that which allows water molecules to be retained. Specifically considering the sludge however, given the historical difficulty in dewatering paper mill sludge, the persistence of water retention is well studied and will remain unchanged in nature, where there is no capacity of further mechanical or chemical dewatering.

Figure 44 shows the samples upon initial laydown, in an outdoor, inclined setting. All pans had a small hole placed in the bottom to allow removal of water to avoid buildup, unevenness, and the potential for decomposition of material through increased water settling. The study area provided both shade and direct view of sunlight at various times during the day and was exposed minimally to human or animal traffic. Figure 43 excludes the Celumulch mixture (leftmost pan) however, however the mixture was added on the same day.

Figure 43 - Outdoor hydroseed trial 1, post plant - day 1. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 44 provides an update from Figure 43, indicating the presence of grass growth 1 week post plant.

Figure 44 – Outdoor hydroseed trial 1 - 1 week post plant. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 45 shows the growth progression one week post plant, with the leftmost pan being that containing 100% soil and to the right 5% sludge. From this view one can see that the left side of the trial has shown the greatest growth over the first week, specifically the first 2 pans containing sludge (5 and 10% sludge).

Figure 45 - Outdoor hydroseed trial 1 - 1 week post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

3 weeks post plant the growth has dramatically improved in all mixtures. Blade length in mixtures containing high percentages of sludge exceed those of lower percentages as seen in Figure 46 where the rightmost mixture contains 100% sludge.

Figure 46 - Outdoor hydroseed trial 1 - 3 weeks post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*),

Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 47 displays further growth over 5 weeks; at this stage all mixtures have provided desirable growth from a qualitative perspective. As with Figure 46, the mixtures containing higher sludge percentages continue to show longer blade lengths. This is further supported by Figure 48, where overgrowth is visible.

Figure 47 - Outdoor hydroseed trial 1 - 5 weeks post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 48 - Outdoor hydroseed trial 1 - 6 weeks post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

All counts were taken on only one side of the bricks which were put in place to avoid the pans blowing away in weather conditions and to maintain place on the incline.

In the weeks following planting, while all samples filled in and produced aesthetically pleasing grass coverage, the sample composed of 100% sludge produced noticeably longer blades of grass than all other samples. While not the densest coverage, the speed of growth was notable and if placed in a larger laydown area would likely be unnoticed. Also, considering the incline plane, the grass in all samples appears to have grown slightly better nearing the bottom of the plate, which is to be expected with initial seed runoff. Comparing all samples this seems to be more problematic in the higher volumes of sludge, however, this could appear more noticeable due to the ‘stringy’ nature of the mixture. This can be later compared with the indoor findings.

The trying weather conditions during these trials have further proven the potential for success as all mixtures germinated to some extent under abnormally dry weather conditions, receiving no additional water to compensate for the dry conditions.

Indoor Trial 1

The indoor trials began much the same as those conducted outdoors. Smaller pans were utilized to simplify the experiment and bricks were not needed as wind would not be problematic in the greenhouse environment. Figure 49 provides a starting point for the trial, showing the experimental setup immediately post plant.

Figure 49 - Indoor hydroseeding trial 1 - 1 week post plant. The yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figures 50 and 51 provide a visual of the experiment 1 week post plant, at this time showing no notable growth. This was initially concerning given the quick progress in the outdoor trial.

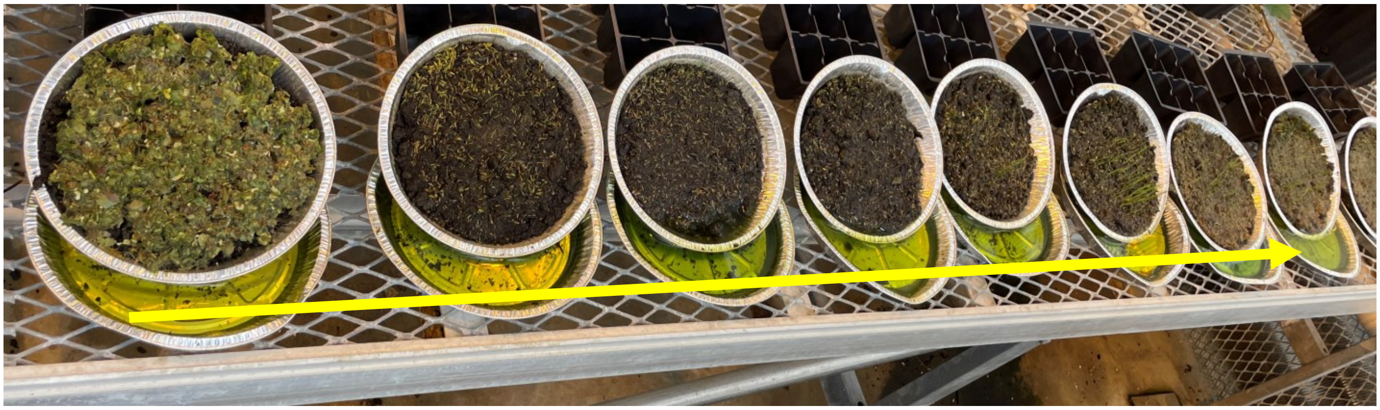


Figure 50 - Indoor hydroseeding trial 1 - 1 week post plant. The yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

No notable growth was seen one week post plant, which was initially concerning given the clear changes seen in the outdoor trial.

Figure 51 - Indoor hydroseeding trial 1 - 2 weeks post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Shortly into the second week of growth, the samples quickly picked up and began aligning with the results seen in the outdoor trial. The most promise was seen, in Figure 52, as being in samples with the highest percentage of sludge, on the rightmost side of the figure.

Figure 52 - Indoor hydroseeding trial 1 - 2 weeks post plant 2 Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

The grass began growing best (quantity and density) in high percentages of sludge, over the first two weeks. Over the duration of the 4-week indoor trial, the samples did not provide consistent outcomes as had been seen in the initial outdoor trial. The sludge-containing samples prevailed throughout the complete duration of the trial, showing dense growth with high blade counts. The angle of incline did affect the placement of growth as notably as in the first outdoor trial. In mixtures containing higher amounts of sludge, toward the lower portion of the pan on the incline, there is a sparsity of sludge, while minimal, this suggests, that when nearing 100% sludge, the seeds are not as tightly held within the material, but instead, are able to be washed away. This could also be due to the time required for runoff to pass, where a small hole at the center of the lower portion of the pan allows for drainage, a buildup may occur allowing seeds to float and be carried away while awaiting space to drain. Overall, the effects of this are minimal and on a larger, landscape scale, this would be estimated to be negligible.

Outdoor Trial 2

For replication, all trials were conducted twice, to ensure consisteny. Figures 53-56 show growth progression over 5 weeks of the experiment in an outdoor environment. The results of this trial aligned with those in Trial 1. Growth began at the top of the plate, this could indicate minimal washaway, as growth may be expected closer to the bottom of the plate if seeds were washed downward on the incline.

Figure 53 – Outdoor hydroseeding trial 2 – 0 days post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 54 - Outdoor hydroseed trial 2 - 1 week post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 55 - Outdoor hydroseed trial 2 - 2 weeks post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 56 - Outdoor hydroseed trial 2 - 5 weeks post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Indoor Trial 2

The follow up indoor trial, was documented initially through Figures 57 and 58. As with the first indoor trial, approximately two weeks were needed prior to first germination. At the two week point, low percentages of sludge showed first germination and in the following weeks, as with previous trials, all mixtures caught up. The mixtures containing higher percentages of sludge showed the longest blade growth.

Figure 57 – Indoor hydroseed trial 2 - 1 week post plant. Yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 58 – Indoor hydroseed trial 2 - 2-week post plant. The yellow arrow denotes direction of increasing sludge percentage. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Figure 59 provides visual weekly changes seen in the second indoor gras trial.

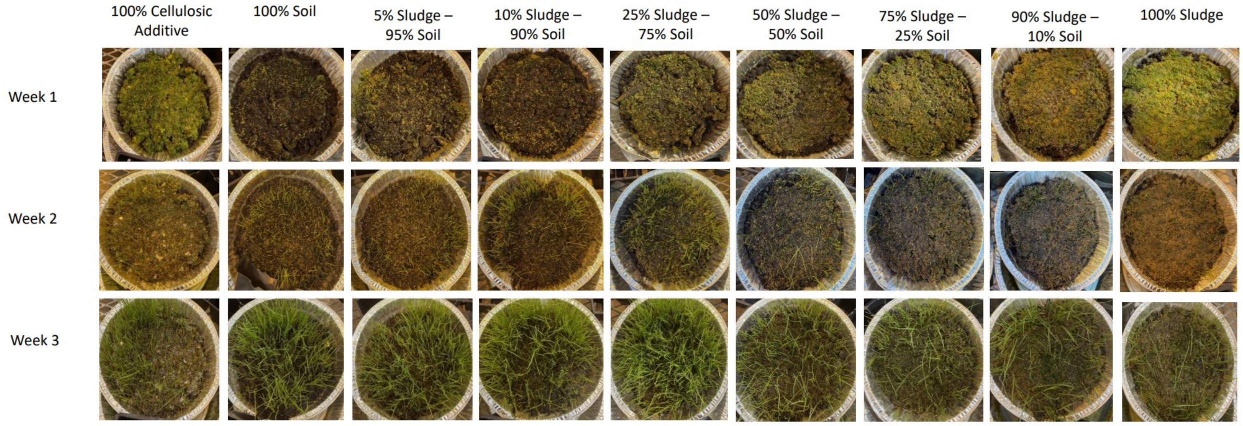


Figure 59 – Weekly grass growth during IT2. Growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

Table 17 provides a comparison between CCME guidelines, sample base mixtures, and harvested blades of grass for indoor trials where Table 18 provides similar information for the outdoor hydroseeding trials.

Table 17 - Government Residual Regulations in comparison to PHP sludge analytes for IT1 and IT2 (adapted from Anderson, 2015) (all values in mg/kg)

Analyte	Average PHP Residual Analysis *2015 basis	100% Sludge (base mixture)	25% Sludge-75% Soil (base mixture)	100% Cellulosic Additive	100% Soil	10% Sludge-90% Soil	25% Sludge-75% Soil	50% Sludge-50% Soil	CCME Compost & NS Biosolids Class B (MAX)	CCME Compost & NS Biosolids Class A (MAX)
Arsenic (mg/kg)	0	<1	<1	0.05 0.07	0.11 0.07	0.11 0.08	0.08 0.07	0.06 0.06	75	12
Cadmium (mg/kg)	0	0.12	0.12	0.017 0.006	0.021 0.005	0.008 0.007	0.007 0.007	0.012 0.007	20	3
Chromium (mg/kg)	3	4	2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	1060	210
Cobalt (mg/kg)	0	0.2	0.5	0.04 0.04	0.06 0.02	0.04 0.03	0.02 0.03	0.02 0.06	150	34
Copper (mg/kg)	3	5	28	2.6 1.3	1.8 1.2	1.1 1.3	1.2 1.2	1.4 1.1	760	400
Lead (mg/kg)	0.7	1.2	2.1	0.14 0.05	0.10 <0.02	0.03 <0.02	<0.02 <0.02	0.03 0.05	500	150
Molybdenum (mg/kg)	0	1	1.3	0.31 0.12	0.28 0.13	0.13 0.16	0.19 0.17	0.4 0.18	20	5
Nickel (mg/kg)	0	<1	1	0.4 0.3	0.5 0.2	0.4 0.3	0.3 0.2	0.3 0.3	180	62
Selenium (mg/kg)	0.0	<1	<1	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	14	2
Zinc (mg/kg)	18	12	38	8.4 6.3	9.8 6.7	6.8 6.9	7.3 6.8	8.9 6.8	1850	700
Fecal Coliforms (MPN/g dry)	2,075,000	<3	<3	/	/	/	/	/	<2,000,000	<1,000

Table 18 Government Residual Regulations in comparison to PHP sludge for OT1 and OT2 (adapted from Anderson, 2015) (all values in mg/kg)

Maximum Allowable Levels **Trace Elements (Max)**	**Average PHP Residual Analysis** ***2015 basis**	**100% Sludge (base mixture)**	**25% Sludge-75% Soil (base mixture)**	**100% Cellulosic additive**	**100% Soil**	**10% Sludge-90% Soil**	**25% Sludge-75% Soil**	**50% Sludge-50% Soil**	**CCME Compost & NS Biosolids Class B**	**CCME Compost & NS Biosolids Class A**
Arsenic (mg/kg)	0	<1	<1	0.05 0.04	0.02 0.04	0.03 0.04	0.03 0.05	0.04 0.03	75	12
Cadmium (mg/kg)	0	0.12	0.12	0.025 0.012	0.027 0.011	0.034 0.017	0.018 0.011	0.021 0.009	20	3
Chromium (mg/kg)	3	4	2	0.4 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	1060	210
Cobalt (mg/kg)	0	0.2	0.5	0.11 0.04	<0.02 <0.02	<0.02 0.04	<0.02 0.03	<0.02 0.02	150	34
Copper (mg/kg)	3	5	28	5.2 2.2	1.3 1.5	1.7 2.2	1.6 2.0	2.1 1.7	760	400
Lead (mg/kg)	0.7	1.2	2.1	0.39 0.14	0.04 0.03	0.03 0.09	0.03 0.08	0.04 0.07	500	150
Molybdenum (mg/kg)	0	1	1.3	0.28 0.31	0.31 0.42	0.49 0.39	0.48 0.48	0.61 0.31	20	5
Nickel (mg/kg)	0	<1	1	0.4 0.3	0.3 0.3	0.3 0.4	0.3 0.3	0.3 0.2	180	62
Selenium (mg/kg)	0.0	<1	<1	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	<0.2 <0.2	14	2
Zinc (mg/kg)	18	12	38	15.8 9.8	12.4 12.9	17.7 15.2	13.2 14.4	23.6 9.6	1850	700
Fecal Coliforms (MPN/g dry)	2,075,000	<3	<3	/	/	/	/	/	<2,000,000	<1,000

Table 19 provides transfer factor values for indoor hydroseeding trials while Table 20 does the same for outdoor trials.

Table 19 - Heavy metal content found in grass blade samples grown in 25% sludge/75% soil mixtures, and the resulting transfer factor ratios for metals over two replicates of indoor trials (IT1 and IT2).

	Base Mixture (mg/kg)	**IT1 (mg/kg)**	**IT2 (mg/kg)**	**TF IT1**	**TF IT2**	**TF Values from Yan *et al.*, Study (2012)**
Aluminum	1650	20.8	16.9	0.0126	0.0102	
Antimony	< 0.1	< 0.02	< 0.02	N/A	N/A	
Arsenic	< 1	0.08	0.07	N/A	N/A	
Barium	38	7.8	4.6	0.2053	0.1211	
Beryllium	< 0.1	< 0.02	< 0.02	N/A	N/A	
Bismuth	< 1	< 0.2	< 0.2	N/A	N/A	
Boron	9	2.3	1.8	0.2556	0.2	
Cadmium	0.12	0.007	0.007	0.0583	0.0583	1.34
Calcium	18200	1340	860	0.0736	0.0473	
Chromium	2	< 0.2	< 0.2	N/A	N/A	
Cobalt	0.5	0.02	0.03	0.04	0.06	
Copper	28	1.2	1.2	0.0429	0.0429	0.47
Iron	1100	23	22	0.0209	0.02	
Lead	2.1	< 0.02	< 0.02	N/A	N/A	0.18
Lithium	0.6	0.03	0.02	0.05	0.0333	
Magnesium	2330	386	339	0.1657	0.1455	
Manganese	438	14.9	13.5	0.034	0.0308	
Molybdenum	1.3	0.19	0.17	0.1462	0.1308	
Nickel	1	0.3	0.2	0.3	0.2	
Potassium	1330	3320	3970	2.4962	2.985	
Rubidium	1.9	4.89	3.7	2.5737	1.9474	
Selenium	< 1	< 0.2	< 0.2	N/A	N/A	
Silver	< 0.1	< 0.02	< 0.02	N/A	N/A	

	Base Mixture (mg/kg)	**IT1 (mg/kg)**	**IT2 (mg/kg)**	**TF IT1**	**TF IT2**	**TF Values from Yan *et al.*, Study (2012)**
Sodium	770	1020	770	1.3247	1	
Strontium	22	6.3	4	0.2864	0.1818	
Tellurium	< 0.1	< 0.02	< 0.02	N/A	N/A	
Thallium	< 0.1	< 0.02	< 0.02	N/A	N/A	
Tin	< 1	< 0.02	< 0.02	N/A	N/A	
Uranium	0.5	< 0.02	< 0.02	N/A	N/A	
Vanadium	2	< 0.1	< 0.1	N/A	N/A	
Zinc	38	7.3	6.8	0.1921	0.1789	0.63

Table 20 - Heavy metal content found in grass blade samples grown in 25% sludge/75% soil mixtures, and the resulting transfer factor ratios for metals over two replicates of outdoor trials (OT1 and OT2).

	OT1 (mg/kg)	OT2 (mg/kg)	Base Mixture (mg/kg)	TF IT1	TF IT2	TF Values from Yan *et al.*, Study [17]
Aluminum	17.8	80.3	1650	0.0108	0.0487	
Antimony	< 0.02	< 0.02	< 0.1	N/A	N/A	
Arsenic	0.05	0.03	< 1	N/A	N/A	
Barium	16.5	12.2	38	0.4342	0.3211	
Beryllium	< 0.02	< 0.02	< 0.1	N/A	N/A	
Bismuth	< 0.2	< 0.2	< 1	N/A	N/A	
Boron	1.6	1.1	9	0.1777	0.1222	
Cadmium	0.018	0.011	0.12	0.15	0.0925	1.34
Calcium	2560	1720	18200	0.1406	0.0945	
Chromium	< 0.2	< 0.2	2	N/A	N/A	
Cobalt	0.02	0.03	0.5	0.04	0.06	
Copper	1.6	2	28	0.0571	0.0714	0.47
Iron	23	64	1100	0.0209	0.0591	
Lead	0.03	0.08	2.1	0.0143	0.0381	0.18
Lithium	0.05	0.06	0.6	0.0833	0.1	
Magnesium	864	602	2330	0.3708	0.2584	
Manganese	19	20	438	0.0434	0.0457	
Molybdenum	0.48	0.48	1.3	0.3692	0.3692	
Nickel	0.3	0.3	1	0.3	0.3	
Potassium	3430	3730	1330	2.5789	2.8045	
Rubidium	8.23	5.76	1.9	4.3316	3.0316	
Selenium	< 0.2	< 0.2	< 1	N/A	N/A	
Silver	< 0.02	< 0.02	< 0.1	N/A	N/A	
Sodium	1010	1340	770	1.3117	1.7403	
Strontium	9.8	7.7	22	0.4455	0.3500	
Tellurium	< 0.02	< 0.02	< 0.1	N/A	N/A	
Thallium	< 0.02	< 0.02	< 0.1	N/A	N/A	
Tin	< 0.02	0.03	< 1	N/A	N/A	
Uranium	< 0.02	< 0.02	0.5	N/A	N/A	
Vanadium	< 0.1	0.1	2	N/A	0.05	
Zinc	13.2	14.4	38	0.3474	0.3789	0.63

Figure 60 illustrates runoff from the samples collected at the end of the trials, post blade harvest. An increased volume of water was used to test runoff, being 1 L. Runoff was captured in clear buckets (Figure 60); the green coloration is due to food coloring utilized on the grass seeds. IT2 (3 weeks post plant) showed a greater amount of soil in runoff than IT1 (5 weeks post plant), which suggests that a dense root system is not fully formed at 3 weeks post plant, but that by 5 weeks, the system has penetrated the soil layer completely. The low-mid range of sludge percentages displayed the clearest runoff samples, indicating minimal washaway.

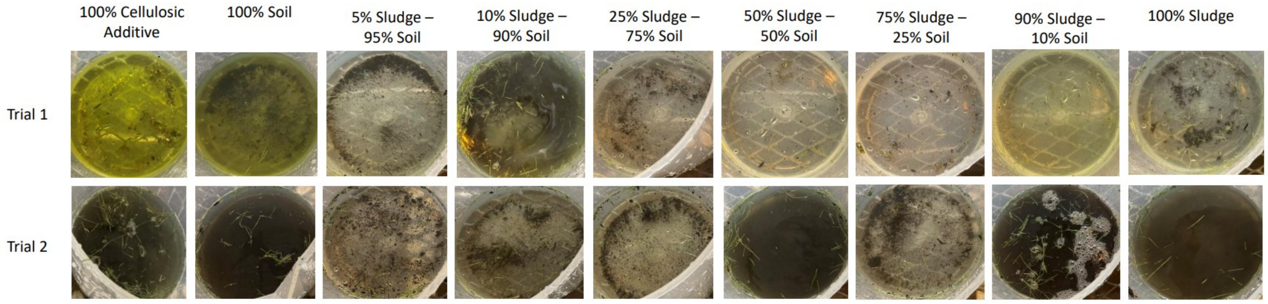


Figure 60 - Photos of runoff following completion of trials.

Figure 61 below shows samples which were utilized in root: shoot analysis. These samples represent portions of soil cake material which were utilized to estmiate whole masses of root material.

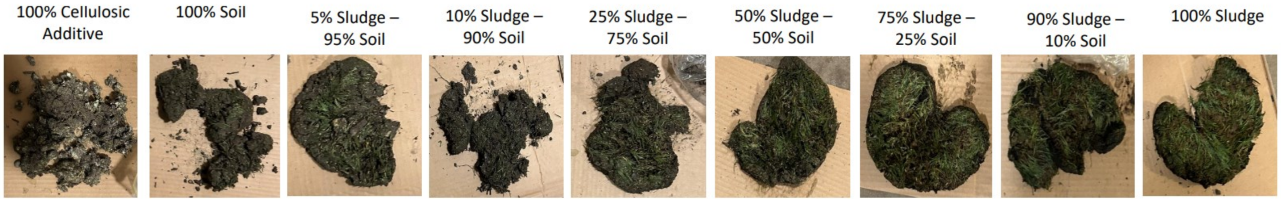


Figure 61 - Samples utilized to estimate root - shoot ratios. Left to right shows increasing sludge percentage.

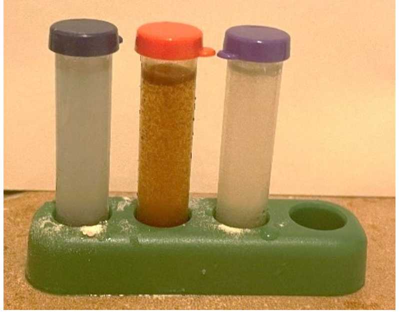
Trial 2 showed a greater amount of soil in runoff, which suggests the need for a greater settling duration, as the samples are still loosely bound. The low-mid range of sludge percentages displayed the clearest runoff samples, indicating minimal washaway showing runoff values from both indoor trial in a volumetric form.

A simple soil test was utilized to visually determine the presence of nitrogen, phosphorous, and potassium. Table 21 displays ratings for each nutrient and next to the vials is the sample used for extraction.

Table 21 – Color-based ratings of soil mixtures considering presence of nitrogen, phosphorous, and potassium.

Base Mixture Composition	Sample Photo	Nitrogen Presence/ Ranking	Phosphorous Presence/ Ranking	Potassium Presence/ Ranking
100% Celumulch		Very Low	Very Low	Low
50% Sludge – 50% Soil		Very Low	Very Low	Low
75% Sludge – 25% Soil		Very Low	Very Low	Low-Medium
90% Sludge – 10% Soil		Very Low	Very Low	Low-Medium

Base Mixture Composition	**Sample Photo**	**Nitrogen Presence/ Ranking**	**Phosphorous Presence/ Ranking**	**Potassium Presence/ Ranking**
100% Sludge		Very Low	Very Low-Low	Low-Medium
100% Soil		Very Low	Very Low	Low-Medium
5% Sludge – 95% Soil		Very Low	Very Low	Low-Medium
10% Sludge – 90% Soil		Very Low	Very Low	Low-Medium

Base Mixture Composition	Sample Photo	Nitrogen Presence/ Ranking	Phosphorous Presence/ Ranking	Potassium Presence/ Ranking
25% Sludge – 75% Soil		Very Low	Very Low-Low	Low-Medium
100% Water - baseline		Very Low	Very Low	Low

From the above photos in Table 21, minute, negligible changes were seen with regards to nitrogen and phosphorous (blue and purple caps). While conducting the experiments, especially upon pouring out the samples, the color of the nitrogen and phosphorus samples did darken, but again, to a negligible degree, indicating very low values in each mixture. The level of potassium did however change notably. Samples darkened in color under the orange cap as the sludge percentage increased, with the highest value indicating low-medium presence of the nutrient.

Table 22 utilizes soil quality data procured by Anderson (2015) and compares it information from the land trial which took place at Port Hawkesbury Paper.

Table 22 - Comparative results from grass follicle metals testing on sludge based hydroseeding patch against CCME Soil Quality Guidelines for protection of human and environmental health (Adapted from Canadian Council of Ministers of the Environment, 2005, Canadian Council of Ministers of the Environment, 2019)

		Soil Quality Guidelines - Concentration (mg/kg dry weight)			
Metal	**Concentration (mg/kg dry weight)**	**Agricultural**	**Residential**	**Commercial**	**Industrial**
Antimony	<2	20	20	40	40
Arsenic	<2	12	12	12	12
Barium	10	750	500	2000	2000
Beryllium	<2	4	4	8	8
Boron	<2	2	N/A	N/A	N/A
Cadmium	<0.3	1.4	10	22	22
Chromium	<2	65	64	87	87
Cobalt	<1	40	50	300	300
Copper	2	63	63	91	91
Lead	<0.4	70	140	260	600

APPENDIX D Plant Trials – Additional Information and Photos – Soil Testing

Seen in Figure 62 are jars containing samples of each mixture composition. The samples were diluted in distilled water, mixed, and left to dilute for 24 hours before measurements occurred. The ratio of soil material to distilled water is 1:2 g/mL

Figure 62 - Soil samples prepped for analysis in distilled water.

Table 23 the nutrients available in a pure sludge sample and a sample of 25% sludge and 75% soil. Analysis of the pulp and paper sludge showed a high level of nitrogen and phosphorous content. While nitrogen and phosphorous amounts are unknown for the 25% soil mixture, considering all other nutrients in Table 25, reduction at highest, would be estimated at half of the 100% sludge value. In the mixture containing 75% soil, additional magnesium and calcium is supplied by the limestone in the soil additive.

The soilless media utilized contains perlite for porosity, Canadian sphagnum peat moss to improve the grade of growth, limestone for pH control, and a wetting agent for surface tension reduction. Table 23 includes values for analytes typically found in fertilizers (Peery, 2022). The fertilizer is abundant in nitrogen, potassium, and phosphorous, compared to sludge.

Table 23 - Nutrients available in Port Hawkesbury Paper's sludge

Nutrient	Amount present in 100% Sludge (mg/kg)	Amount present in a Typical Fertilizer (mg/kg)	Amount present in 25% Sludge – 75% Soil (mg/kg)
Nitrogen	1,700	200,000	-
Calcium	1,850	-	18,200
Potassium	380	~200,000	1,330
Magnesium	330	1,500	2,330
Phosphorous	1,000	~100,000	-
Sodium	1,330	-	770
Boron	15	68	9
Copper	5	36	28
Iron	320	500	1,100
Manganese	1,030	250	438
Zinc	12	25	38

APPENDIX E Plant Trials – Additional Information and Photos – Carrot Trials

Carrots were grown within a greenhouse environment with daily watering and no additional treatments. All were planted and randomized as seen in Figure 63. Approximately 10 seeds were planted in each pot with the goal of germination of at least 5 seeds per pot. Seeds were planted sporadically throughout the pot, ensuring ample space for root development, the seed depth is approximately 1 inch below the free surface.

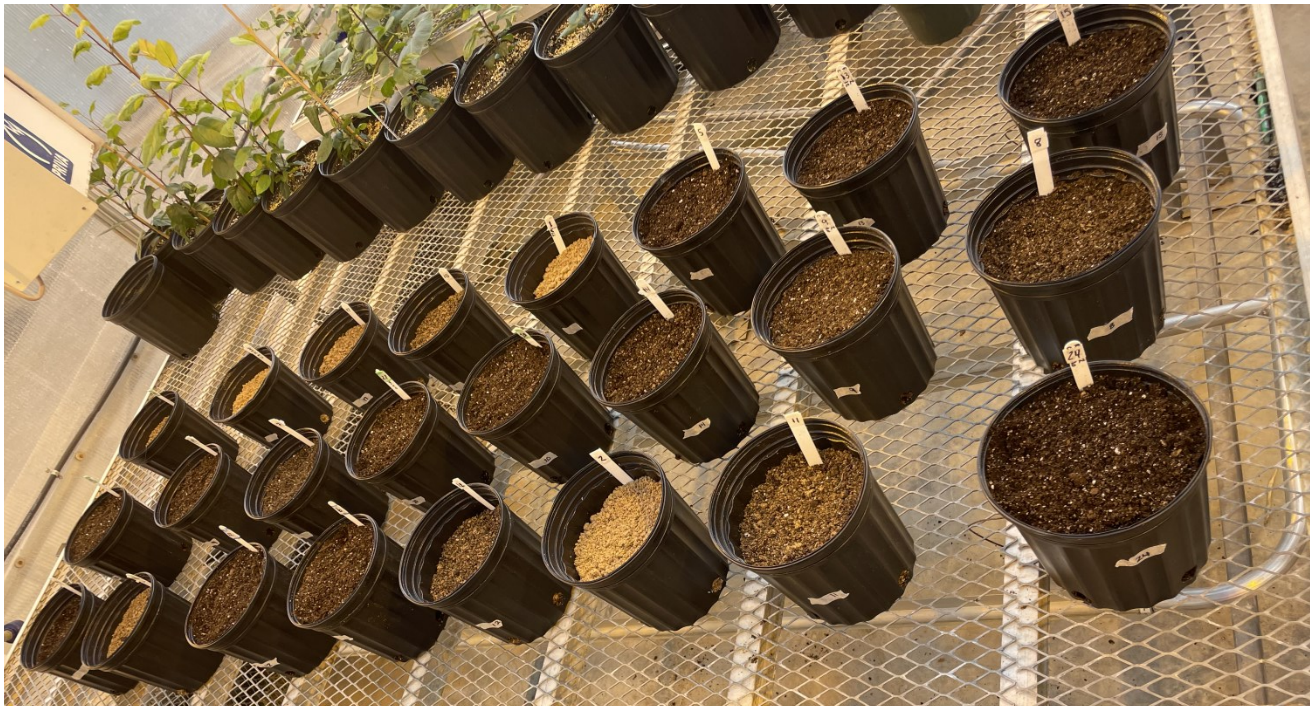


Figure 63 – Carrot *(Daucus carrota)* seeds planted and randomized based on growth medium composition in week 3 of study.

Figure 64 indicates the small presence of growth after one-week post-plant. At this point sprouts were seen in the 100% soil sample (Promix). Figures 64- 66 show various views of early carrot growth progress.

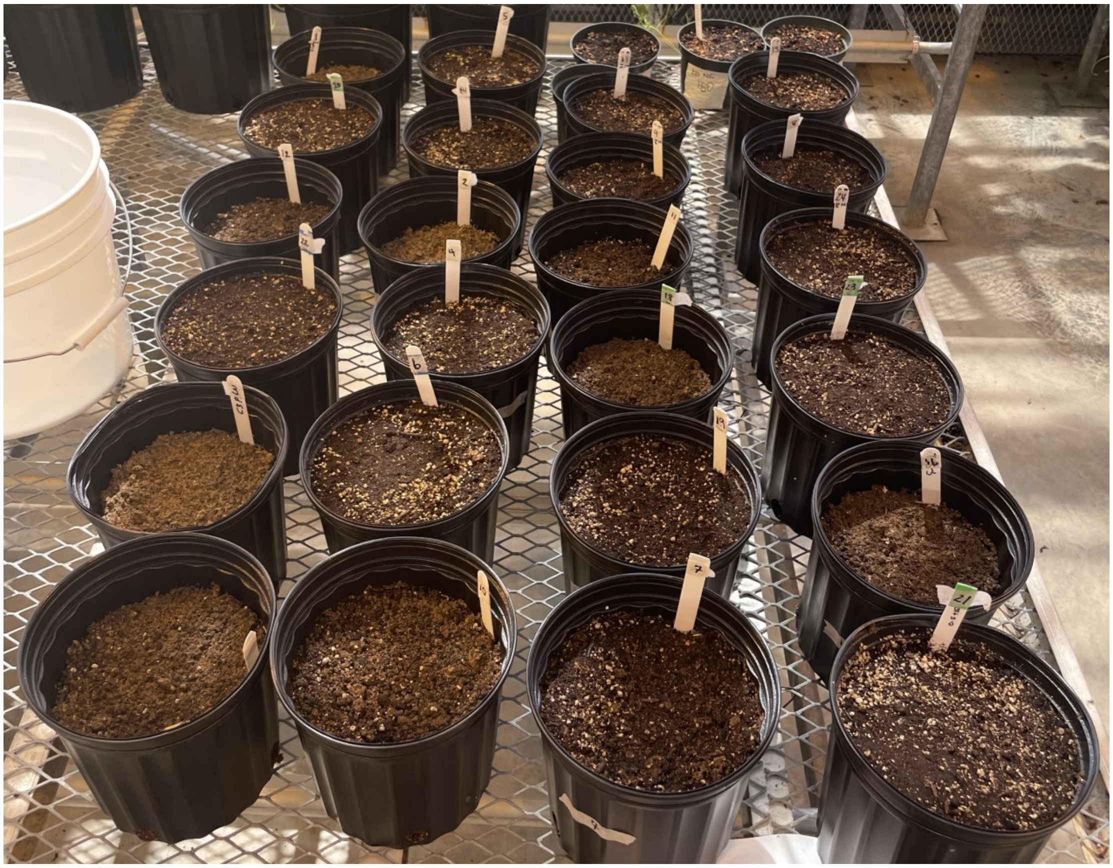


Figure 64 – Carrot *(Daucus carrota)* plants one week after planting. Small sprouts were seen in some pots (Figure 64).

Figure 65 - Example of carrot *(Daucus carrota)* seeds sprouting, circled on photo. Sample shown in photo is grown in 100% soil (Promix).

Figure 66 - Growth progress of carrots *(Daucus carrota)* 3 weeks post-plant.

Carrot germination in 5 and 10% sludge showed capacity for exceeding growth in soil alone. Once surpassing a sludge presence of 50% by mass, germination dramatically decreases to a near zero. This data suggests that sludge becomes detrimental beyond 50% inclusion with soil.

The heartiness of samples was considered by documenting the number of sprouts (germinated seeds) along with ranking the visible health of the sprouts (Figure 67). indicating the mid-low percentages of sludge as being the ideal mixture for carrot growth.

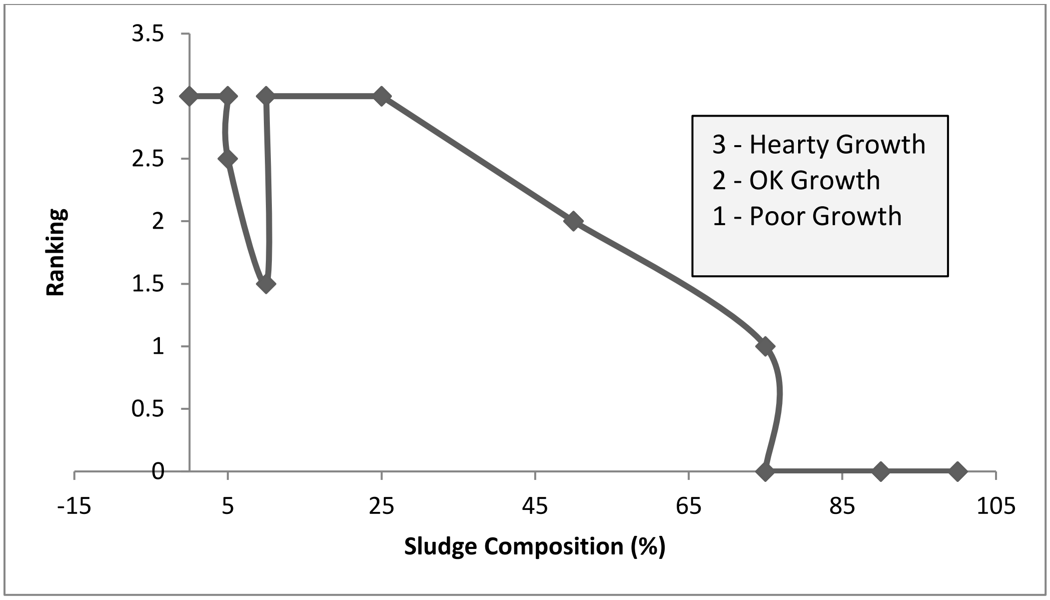


Figure 67 - Heartiness rankings for carrot *(Daucus carrota)* growth.

Through monitoring of growth during the experiment, Figures 68 - 71 indicate that high sludge percentages are not feasible for carrot growth.

Figure 68 –Growth progress of carrots *(Daucus carrota)* 5 weeks post-plant.

Figure 69 – Growth progress of carrots *(Daucus carrota)* 7 weeks post-plant. The arrow indicates the direction of increasing sludge percentage.

Figure 70 - Growth progress of carrots *(Daucus carrota)* 7 weeks post-plant, an alternative view. The arrow indicates the direction of increasing sludge percentage.

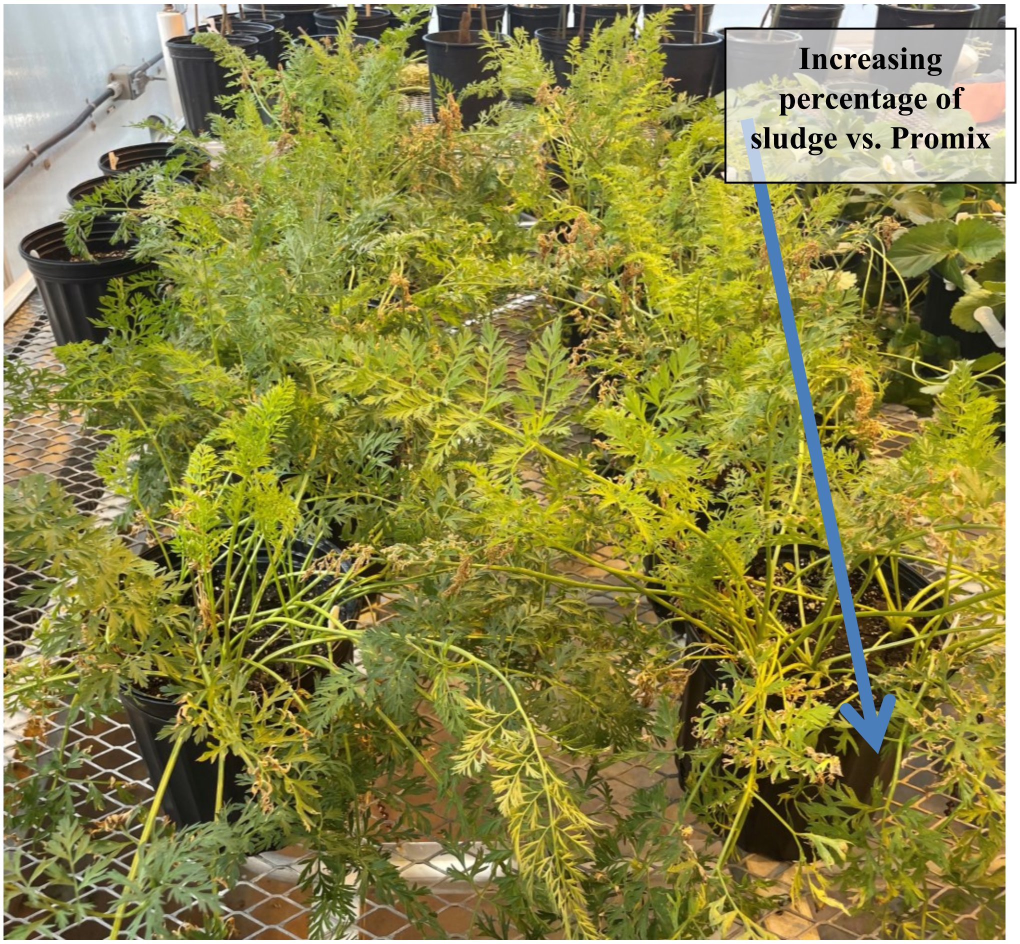


Figure 71 - Growth progress of carrots *(Daucus carrota)* 10 weeks post-plant. The arrow indicates the direction of increasing sludge percentage.

The full spectrum of harvested carrots are pictured in Figure 72.

Figure 72 - Harvested carrots (*Daucus carrota*),

APPENDIX F – Plant Trials – Additional Information and Photos – Lettuce Trials

Trial 1

The lettuce seedlings were first grown in a controlled small scale lab environment seen in Figures 73 – 76 under 80 W lights 24/7 for approximately 4 weeks.

Figure 73 – Lettuce (*Lactuca sativa*) seeds planted in packs of 6, 1-week post-plant.

Figure 74 – Lettuce (*Lactuca sativa*) seedlings progress 2 weeks post-plant.

Figure 75 – Lettuce (*Lactuca sativa*) seedlings progress 3 weeks post-plant.

Figure 76 – Lettuce (*Lactuca sativa*) seedlings progress 4 weeks post-plant.

The lettuce seedlings are then ready to be transplanted into the study medium following 4 weeks of growth (Figure 76). In the transplanting process, ideally one will choose seedlings of similar size, to allow for comparability. In the case of the first trial, this was not possible. To reduce inconsistency, randomization of larger seedlings occurs throughout the replicates. Seedlings mid-transplant are shown in Figures 77-78.

Figure 77 – Lettuce (*Lactuca sativa*) in the transplanting process. In the background are transplanted samples and remaining in the packs are seedlings which have not been utilized due to size inconsistency.

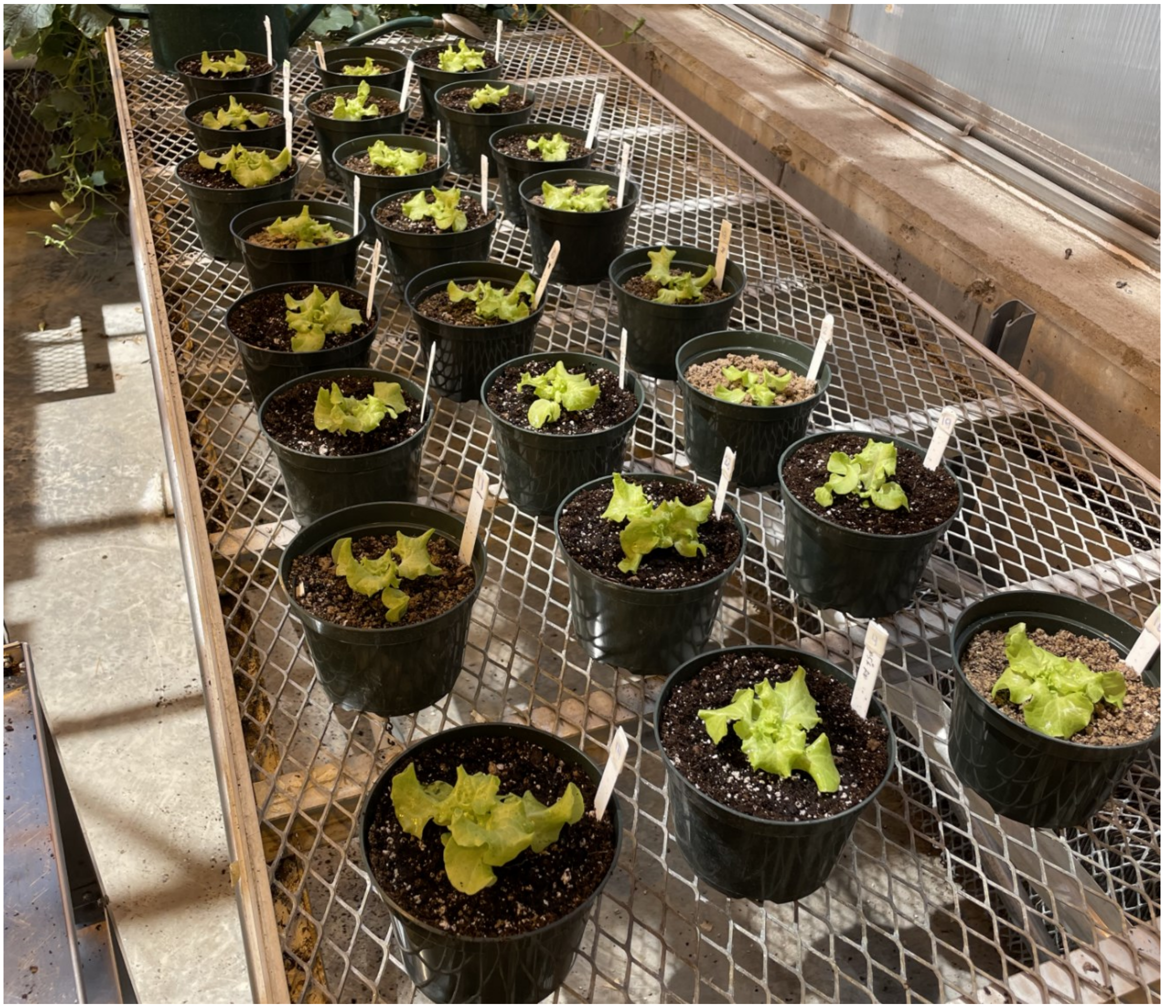


Figure 78 - Transplanted lettuce (*Lactuca sativa*) seedlings 4 weeks post-transplant. The seedlings are organized in a randomized fashion based on growth medium makeup.

The quick degradation of growth in lettuce plants with high percentages of sludge are due to the combined presence of aluminum in high volumes along with the low pH of the sludge. When combined with Promix, the pH of the system is raised above 5 which allows for successful growth and mitigates the effects of the aluminum. Considering the production of the, there is potential for increasing the pH without the addition of Promix, through an additive such as fly ash. Studies on the stop1 protein have indicated that while adverse effects can come from common metals such as cadmium, hypersensitivity was seen in the presence of aluminum (Takahashi, 2012). In this study aluminum presents a concern which, when combined with the low pH of the sludge, can wreak havoc on the plant life. Samples pre-harvest are seen in Figure 79.

Figure 79 – Lettuce (*Lactuca sativa*) heads prior to harvest.

Through harvesting of the lettuce, dead leaves were removed, and a fresh weight was taken. Once complete, the leaves were dried for 3 days at 65°C and weighed, with the difference determining the moisture present.

Figure 80 demonstrates a head of lettuce post-harvest being weighed for its fresh mass. Prior to weighing, roots are removed, and all dead leaf material is extracted.

Figure 80 - Sample of harvested lettuce (*Lactuca sativa*) head.

Trial 2

The second trial was carried out as a replicate to the first, with seedlings first grown in separate containers and transplanted after 4 weeks of growth. Figures 81 – 84 display various stages of lettuce growth.

Figure 81 - Growth progress of lettuce (*Lactuca sativa*) 2 weeks post-transplant.

Figure 82 - Growth progress of lettuce (*Lactuca sativa*) 2 weeks post-transplant

Figure 83 - Growth progress of lettuce (*Lactuca sativa*) 5 weeks post-transplant

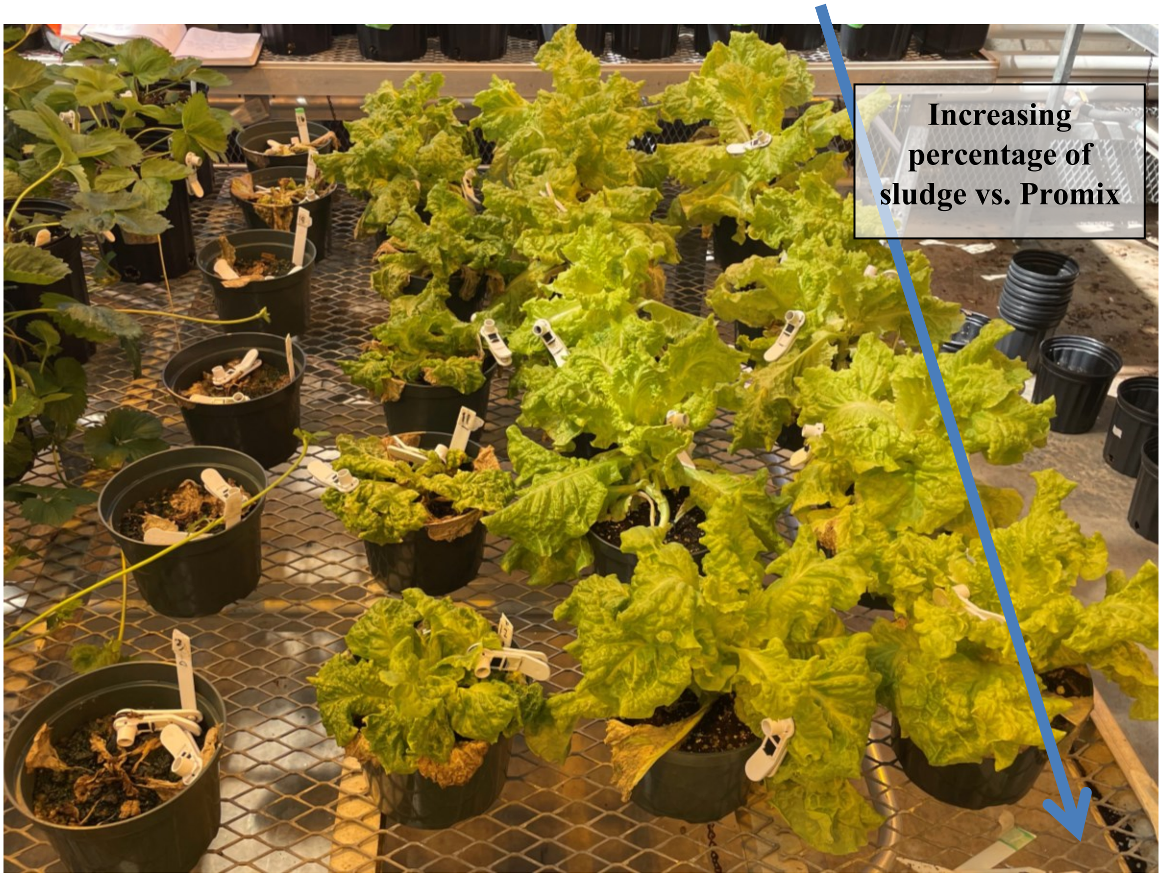


Figure 84 - Growth progress of lettuce (*Lactuca sativa*) 7 weeks post-transplant

Nutrients measured in harvested lettuce samples are presented in Table 24; this data suggests that optimal growth is seen in 25% sludge-soil mixtures.

Table 24 - Nutrients present in lettuce (*Lactuca sativa*) leaves through tissue analysis – average values from the first and second lettuce trials.

Sludge Present (%)	Nitrogen (%)	Calcium (%)	Potassium (%)	Magnesium (%)	Phosphorus (%)	Sodium (%)	Boron (ppm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)
0	2.090	1.031	4.263	0.296	0.564	0.484	19.090	53.400	168.66	47.740
25	5.185	0.818	2.656	0.382	0.822	0.571	24.445	107.175	194.955	78.330
75	6.415	0.402	1.409	0.207	0.711	0.571	-	70.640	152.560	48.915

An ANOVA analysis of the data in Table 9 is found in Table 25. Calcium is the only analyte shown to positively correlate with the percentage of sludge included.

Table 25 – ANOVA analysis of nutrients present in lettuce leaves.

% Analyte	Source	DF	Sum of squares	Mean squares	F	P-value	R^2
Nitrogen	Model	1	8.175	8.175	4.652	0.276	0.823
	Error	1	1.757	1.757			
	Corrected Total	2	9.933				
Calcium	Model	1	0.205	0.205	28655.413	**0.004**	1
	Error	1	0.000	0.000			
	Corrected Total	2	0.205				
Potassium	Model	1	3.818	3.818	13.815	0.167	0.932
	Error	1	0.276	0.276			
	Corrected Total	2	4.094				
Magnesium	Model	1	0.007	0.007	0.781	0.539	0.438
	Error	1	0.009	0.009			
	Corrected Total	2	0.015				
Phosphorous	Model	1	0.005	0.005	0.193	0.737	0.162
	Error	1	0.028	0.028			
	Corrected Total	2	0.033				
Sodium	Model	1	0.003	0.003	1.333	0.454	0.571
	Error	1	0.002	0.002			
	Corrected Total	2	0.005				
Iron	Model	1	25.033	25.033	0.017	0.918	0.017
	Error	1	1482.892	1482.892			
	Corrected Total	2	1507.925				
Manganese	Model	1	271.552	271.552	0.421	0.633	0.296
	Error	1	644.439	644.439			
	Corrected Total	2	915.991				
Zinc	Model	1	14.544	14.544	0.025	0.901	0.024
	Error	1	586.247	586.247			
	Corrected Total	2	600.790				

APPENDIX G Plant Trials – Additional Information and Photos – Strawberry Trial

Strawberry seedlings were chosen based upon consistency in appearance, with chosen transplants ideally being without flowers. Regular qualitative and quantitative data was collected. Figure 85 depicts the strawberry seedlings upon pickup, prior to transplant. Figure 86 are the plants immediately post-transplant. Considerations when planting included randomizing seedlings from each box of 4, in case any seedlings had been exposed to more optimal conditions, especially given that the growth of seedlings occurred via a second party greenhouse.

Figure 85 - Charlotte ever bearing strawberry (*Fragaria* × *ananassa*) seedlings prior to transplanting.

Figure 86 - Strawberry (*Fragaria* × *ananassa*) seedlings following transplanting.

Figure 87 depicts the detrimental state of strawberry plants grown in 100% sludge, seen on the left of the photo. The wilting of the plants continued through the trial and ultimately were removed. The reason for rapid deterioration could be linked to the water retention characteristics of the sludge. The roots may be suffocating in this environment, causing wilting (Hailey, 2023).

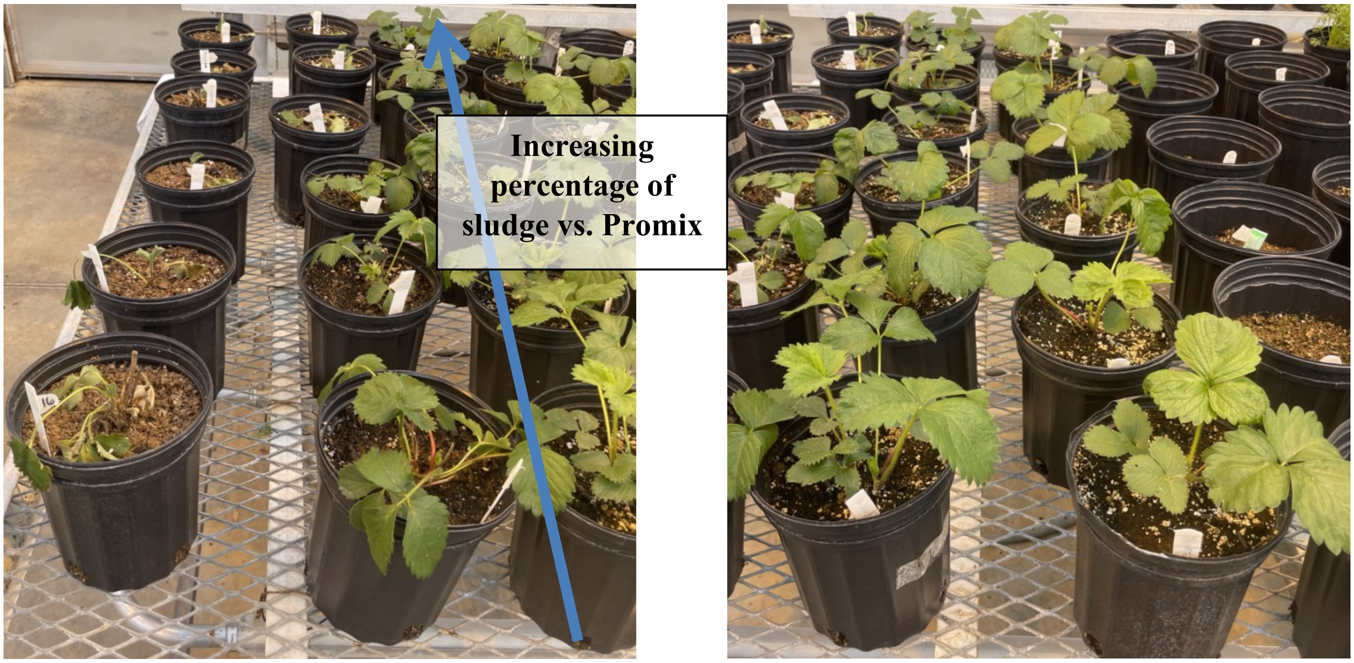


Figure 87 - Strawberry (*Fragaria* × *ananassa*) plants 1-week post-transplant.

Figures 88 - 90 show further growth progress.

Figure 88 – Growth progress of strawberry (*Fragaria* × *ananassa*) plants, 4 weeks post-transplant.

Figure 89 - Growth progress of strawberry (*Fragaria* × *ananassa*) plants, 6 weeks post-transplant.

Figure 90 - Growth progress of strawberry (*Fragaria* × *ananassa*) plants, 6 weeks post-transplant, an alternate view.

Harvested strawberries are shown in Figure 91.

Figure 91 – Samples of harvested strawberries (*Fragaria* × *ananassa*).

Figure 92 displays root systems extracted from strawberry plants.

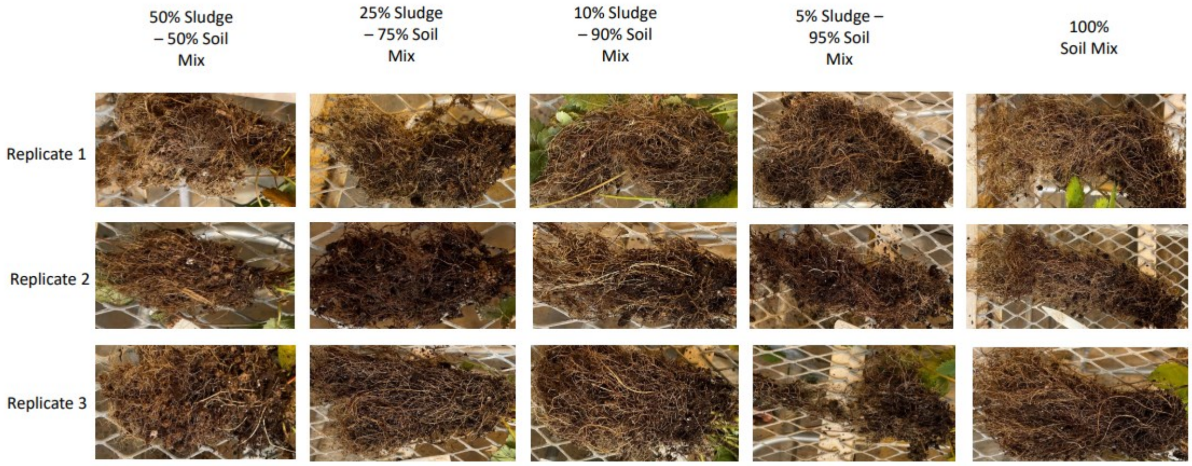


Figure 92 - Root systems extracted from strawberry (*Fragaria* × *ananassa*) plants.

Figure 93 displays the number of berries harvested versus the sludge percentage present in the growth media. Also considered in Figure 93 is the time to ripeness, seen along the horizontal axis. The greatest number of berries were harvested from the 50% sludge mixture, and the date of first fruit appearance occurred earliest in the 5% sludge mixture, occurring almost 10 days before both the 25 and 0% sludge mixtures. While none of the plants produced a significant number of strawberries, the sludge mixtures were competitive in diameter and exceeded the hardness of the soil-based mixture. When considering desirable hardness values of strawberries, a broad range exists, between 4.202–44.382 N (Pădureț *et al.,* 2017).

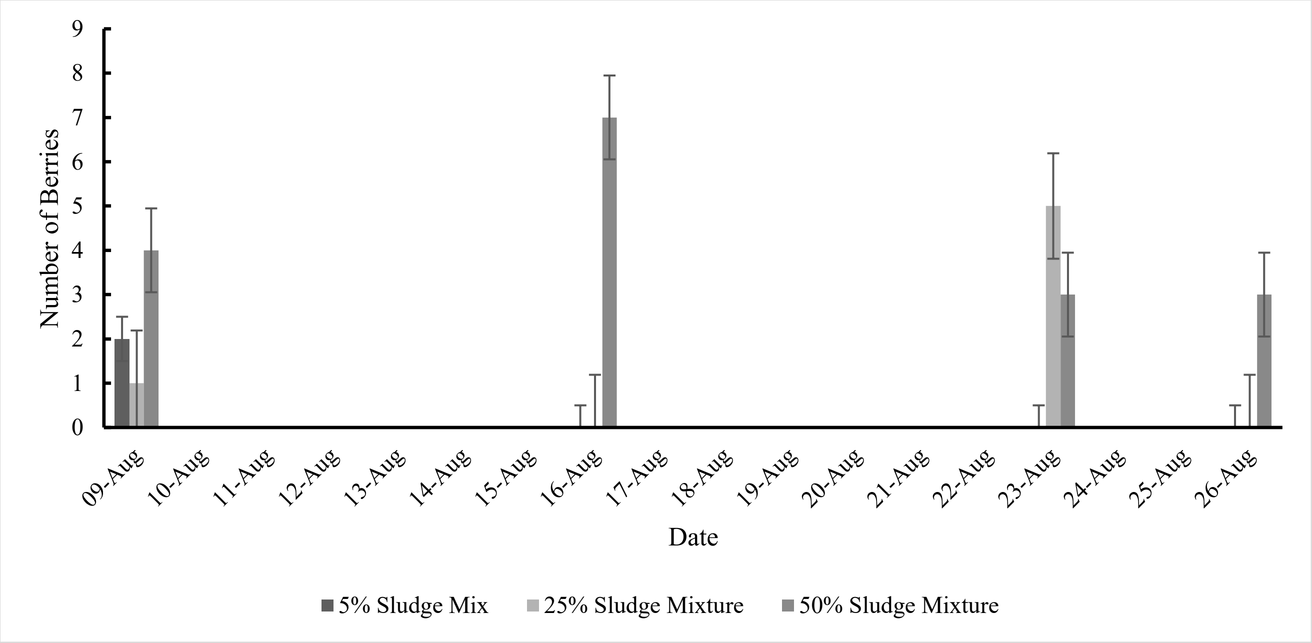


Figure 93 - Strawberry (*Fragaria* × *ananassa*) characteristics dependent upon sludge presence in the sample soil media.

APPENDIX H Seasonal Sludge Metals Considerations – Full Data Set

Table 26 – Metals Testing Outputs on PHP's Sludge Product

Analyte	November 2019 (mg/kg)	May 2019 (mg/kg)	May 2022 (mg/kg)
Aluminum	1200	1860	3670
Antimony	<1	<1	< 0.1
Arsenic	2	3	< 1
Barium	43	50	98
Beryllium	<2	<2	< 0.1
Boron	15	88	15
Cadmium	<0.3	<0.3	0.12
Chromium	4	4	4
Cobalt	<1	1	0.2
Copper	24	4	5
Iron	597	1290	320
Lead	1.5	1.6	1.2
Lithium	<5	7	0.2
Manganese	474	506	1030
Molybdenum	<2	<2	1.0
Nickel	2	3	< 1
Selenium	<1	<1	< 1
Silver	<0.5	<0.5	< 0.1
Strontium	19	267	10
Thallium	<0.1	<0.1	< 0.1
Tin	8	9	5
Uranium	0.9	0.7	0.7
Vanadium	5	4	4
Zinc	29	9	12

APPENDIX I – Water Tests on PHP's Streams

Table 27 - Water tests completed with various streams at PHP. Testing performed by AGAT Laboratories.

Standard Water Analysis + Total Metals						
Sample Description			**Primary Clarifier Overflow**	**Primary Sludge**	**Main Outfall**	**Secondary Sludge**
Date Sampled			**07/06/2017**	**07/06/2017**	**07/06/2017**	**07/06/2017**
Parameter	**Unit**	**RDL**	**8543479**	**8543481**	**8543483**	**8543504**
pH			6.04	5.82	8.02	6.46
Reactive Silica as SiO2	mg/L	0.5	70.3	79.0	24.0	21.2
Chloride	mg/L	10	15	17	26	27
Fluoride	mg/L	1.2	1.2	1.4	<1.2	<1.2
Sulphate	mg/L	20	204	212	187	775
Alkalinity	mg/L	5	394	381	753	301
True Color	TCU	5	785	423	585	311
Turbidity	NTU	0.1	933	NA	14.1	11,100
Electrical Conductivity	umho/cm	1	2,150	2,110	1,890	2,310
Nitrate + Nitrite as N	mg/L	0.5	<0.5	<0.5	<0.5	<0.5
Nitrate as N	mg/L	0.5	<0.5	<0.5	<0.5	<0.5
Nitrite as N	mg/L	0.5	<0.5	<0.5	<0.5	<0.5
Ammonia as N	mg/L	0.03	0.28	<0.03	0.04	18.0
Total Organic Carbon	mg/L	0.5	1,510	1,310	188	240
Ortho-Phosphate as P	mg/L	0.01	0.98	0.37	2.16	15.6
Total Sodium	mg/L	15	564	594	453	481
Total Potassium	mg/L	0.1	35.2	18.6	19.5	71.2
Total Calcium	mg/L	0.1	22.4	43.6	15.1	173
Total Magnesium	mg/L	0.1	5.4	6.0	3.7	29.5
Bicarb. Alkalinity (as CaCO3)	mg/L	5	394	381	753	301
Carb. Alkalinity (as CaCO3)	mg/L	10	<10	<10	<10	<10
Hydroxide	mg/L	5	<5	<5	<5	<5
Calculated TDS	mg/L	1	1,090	1,140	1,160	1,830
Hardness	mg/L		78.2	134	52.9	553
Langelier Index (@20C)	NA		-1.71	-1.65	0.38	-0.54
Langelier Index (@ 4C)	NA		-2.03	-1.97	0.06	-0.86
Saturation pH (@ 20C)	NA		7.75	7.47	7.64	7.00

Sample Description			**Primary Clarifier Overflow**	**Primary Sludge**	**Main Outfall**	**Secondary Sludge**
Date Sampled			**07/06/2017**	**07/06/2017**	**07/06/2017**	**07/06/2017**
Parameter	**Unit**	**RDL**	**8543479**	**8543481**	**8543483**	**8543504**
Saturation pH (@ 4C)	NA		8.07	7.79	7.96	7.32
Anion Sum	me/L		12.5	12.5	19.7	22.9
Cation sum	me/L		27.3	30.4	21.5	39.1
% Difference/ Ion Balance (NS)	%		37.1	41.6	4.4	26.1
Total Aluminum	ug/L	1110	439	9,850	294	19,700
Total Antimony	ug/L	2	<2	<2	<2	<2
Total Arsenic	ug/L	2	<2	<2	<2	7
Total Barium	ug/L	140	307	554	94	2420
Total Beryllium	ug/L	2	<2	<2	<2	3
Total Bismuth	ug/L	2	<2	<2	<2	<2
Total Boron	ug/L	5	79	82	32	1270
Total Cadmium	ug/L	0.017	3.02	2.02	1.66	2.87
Total Chromium	ug/L	1	13	56	4	121
Total Cobalt	ug/L	1	1	3	<1	6
Total Copper	ug/L	1	44	104	18	155
Total Iron	ug/L	50	723	3130	687	3780
Total Lead	ug/L	0.5	6.9	8.3	3.9	17.9
Total Manganese	ug/L	2	6,830	4,300	4,820	44,600
Total Molybdenum	ug/L	2	<2	4	<2	47
Total Nickel	ug/L	2	6	12	4	23
Total Phosphorous	mg/L	0.02	1.82	2.28	2.67	107
Total Selenium	ug/L	1	<1	<1	<1	4
Total Silver	ug/L	0.1	0.6	5.2	0.1	9.5
Total Strontium	ug/L	5	147	277	82	844
Total Thallium	ug/L	0.1	0.2	0.3	0.1	1.1
Total Tin	ug/L	2	13	42	<2	80
Total Titanium	ug/L	2	9	52	6	27
Total Uranium	ug/L	0.1	<0.1	0.3	2.5	31.3
Total Vanadium	ug/L	2	10	19	10	85
Total Zinc	ug/L	5	510	376	370	652

APPENDIX J – Business Considerations

Considering the value to be gained from this study, it is unlikely that paper mill sludge material will be utilized for domestic purchase, however, it would prove useful for large scale hydroseeding operations such as along the sides of highways.

Determination of optimal process efficiency must account for social, economic, and environmental benefits and concerns (Mikkelsen, 2011). The specific plant productivity relies upon the harvest effectiveness. For grass, effectiveness would ultimately relate to coverage and aesthetic appearance. Regulatory needs must be considered, including a nutrient breakdown, metals, etc. Labor and energy areas are also considered in a growth process. This is then followed by the potential for profit, the typical business cases based upon payback periods. Finally, sustainability of the soil and environment/ eco-system are considered (Bruulsema *et al*., 2008 and Mikkelsen, 2011).

With PHP's sludge, a case can be made for the slow release of nutrients which links from the hydroseeding chapter to the late-stage spurt in growth seen in both the indoor and outdoor trials. In both cases, the mid-low percentages of sludge indicated early/ first germination, however, in the weeks following, the high percentages of sludge quickly caught up and surpassed the growth of all other mixtures with the product indicating long and consistent blade length. Slow-release materials are notably best in cases where leachate and flooding can be a problem (Liu *et al.,* 2021). Given the end goal of hydroseeding use on highways, there is an increased chance of runoff due to the incline-plane. While Slow-Release Fertilizers (SRFs) are typically engineered to control release rates, not all materials can be controlled such as those based on manure (Liu *et al.,* 2021). These manure-based fertilizers can still be classified as SRFs, however, they're often less controllable. An understanding of the environmental conditions can also render a SRF useless if the temperature and moisture meet the correct combination needed to promote the release of nutrients through microbial activity. Common fertilizers allow for quick release of nutrients which often require multiple applications during a growing season due to the likelihood of lost, or diminished value through environmental conditions. To ensure the best fertilizer is chosen for its application, one must understand the specific needs of each plant during all growth stages. Lui *et al*., (2021) has demonstrated the idea growth curve indicating that nutrient release and uptake would ideally act concurrently through application of fertilizer.

Grass, as the focus plant, is agreeable to many conditions, a hearty plant of choice. Remembering that hydroseeding is already possible with the conventional methods, the slow release of nutrients may act as the competitive factor in choosing sludge as opposed to the typical cellulosic additive, such as Celumulch.

Organic manure has been studied for valorization as a fertilizer (Ball *et al*., 2004), and with similar characteristics to paper mill sludge, such information has the potential to better explain the similarities seen in the sludge- based growth trials.

Referring to Chapter 4, approximately \$2.00 per ft^2, assuming a 1000 ft^2 laydown area the total cost would be \$2,000. Assuming a current cost of approximately \$10.00 per tonne to transport sludge to an onsite landfill site at Port Hawkesbury Paper and considering the ideal application rates projected in chapter 4, PHP has an opportunity for benefit through utilization of the sludge rather than transport. Additionally, a typical 40 lb bale of hydroseeding material (shredded newsprint) costs around \$30. Again, this shows potential for value in reuse. Appendix B provides original calculations undertaken upon considering the need for diversion of PHP's sanitary sewer, to allow for diversity in end use of sludge. These calculations provided a case for the sale of the paper mill sludge in the capacity of a soil amendment. Revisiting this project charter, the need for a sanitary sewer diversion can be deemed unnecessary, as the hydroseeding application lab results have indicated a minimal presence of e-coli, below concerning levels for all applications.

Cost Considerations

Figure 94 utilizes potential cost and profit values based on a sludge production value of 200 wet tonnes per day over a year (estimated 250 working days). The ventures of hydroseeding and soil amendment, based upon the land trials are estimated to have a profit of 40 and 8 times that of the current trucking costs at PHP; the columns in this figure are indicative of 60% of the calculated value forsale of all sludge product. 60% was chosen to provide a contingency value to allow for bagging, freight charges, etc. Costs for the hydroseed and amendment were based upon current market pellets and hydroseed mulch. The comparison value for trucking was formulated from a tonnage-based value currently utilized by PHP for transport to on an on-site landfill. The cost of sludge removal at PHP has risen since this trial was undertaken, with an increase of approximately 25%. The increase in pricing further supports the need to determine an end use for the sludge.

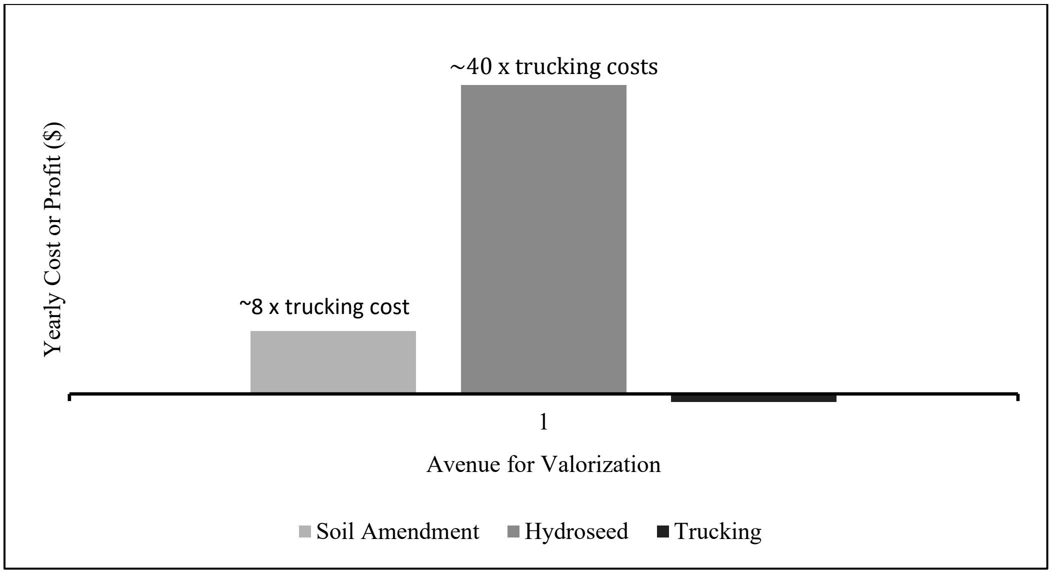


Figure 94 - Potential profit and cost of various ventures for paper mill sludge end use based upon land application trial (based on 2020 pricing).

Compared to other methods of growing grass, such as sodding, hydroseeding a more cost-effective choice as the price of 1 pallet of sod to cover 640 ft^2 is just under $500 based upon from a typical publicly accessible venue website, compared to the same expanse in hydroseeding is almost $1,300 for the same square footage, at approximately $2.00 per ft^2 based upon Rietzel Landscape and Concrete Contractors, an Atlantic Canadian business' website. The purchase price for sod appears drastically below that of hydroseeding, however, the hydroseeding price is a 'catch all' price, whereas the sod price is a materials price. Labor involved in the laydown of sods is often costly, for example, Green Warriors Landscaping indicates the typical residential sod installation cost ranges from $1.80 – 4.00 per ft^2, which is equivalent or greater than that of the typical hydroseeding cost.

Safety Considerations

As discussed earlier in Chapter 2, depending upon the application (grass vs. consumables) the growth media would be required to align with government regulations and approval would need to be sought prior to use. The CCME and CFIA work in collaboration to develop guidelines for safe use and transport of soils or soil amendments. The sludge product PHP produces would require formal approval under the Fertilizers Act. This process involves proof of components, which is important as any notable changes must be reported and would require re-approval and re-application. The forms involved require indication of intended uses, such as indication of the crop type. The time to application is also notable as 5 years of metals tests on the growth media should be provided to ensure consistency. Potential hazards of application must also be clearly described. The application process is well described on the Government of Canada website (Government of Canada, 2021).

Following regulatory guidelines is crucial to maintain environmental and human health. Groundwater can be a source of concern for living beings in close proximity to sites utilizing fertilizers or amendments (Easton & Petrovic, 2004). Through suggested further testing, variables such as incline and treatment regime (water, application, etc.) should be taken into account. Literature suggests that during plant establishment, which occurs early in the process of fertilization, a notable volume of nutrients may be lost to runoff (Easton & Petrovic, 2004). Potential users should consider long-term testing to establish a data set under numerous conditions, ensuring the runoff and plant degradation or slow-release fertilizer behaviour do not pose a threat to the environment or consumers.

If issues such as pH exist, the addition of lime can be used. Hale *et al.'s* (2020) study also indicated, compared to ash (commonly used for plant growth), the use of lime produced a low concentration of aluminum in the soil, which is positive for plant growth.

Further information can be found in Appendix D.

Additional Information

Reflecting upon mixtures presented in Chapter 4, the specific sludge applications rates would range from 0 kg/ m^2 to approximately 2 kg/m^2 based upon the assumption that mixing with soil does not occur prior to spraying.