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

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Research Article

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

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Abstract

Pulp and paper mill sludge is composed of cellulosic waste and clay, and rich in microorganisms that can benefit horticulture. However, its application in horticulture has received less research attention. 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, 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 of Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra)*, Perennial (*Lolium perenne)* and Annual Ryegrass *(Lolium multiflorum*). Seeding with a top layer of soil and 5 to 75% sludge gave the best outcome using a cellulosic additive after 3 weeks of growth. Mixtures containing 5- 25% sludge resulted in the quickest seed germination rate. The cellulosic additive has the capacity to retain a higher volume of water but requires 15 times more material by volume. An increase in sludge increased water retention by 20%. Overall, the cellulosic additive in hydroseeding applications can be replaced by sludge without plant detriment. However, further testing is needed to determine long-term effects.

Keywords: Waste Valorization, Pulp and Paper Sludge, Waste Reuse, Industrial Sustainability, Hydroseed

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.

Graphical Abstract

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 [1]. Sludge is currently disposed of using either dewatering and landfilling or 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 [2]. An alternative valorization pathway that has recently been explored for this solid waste material is use as a soil amendment. O'Brien *et al.,* [3], investigated the use of paper mill sludge generated from a tissue and towel producing industry (utilizing recycled, deinked newsprint) with a local sewage stream included, combined with soil mixtures for the growth of corn (*Zea mays L.*). The findings of that study showed that the 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 [4] where nursey grown plants were shown to flourish in aged or composted sludge from deinked newspaper mills. However, introduction of supplemental nitrogen was suggested to facilitate plant growth and support photosynthesis.

Sludge waste provides a water-rich organic material equipped with nutrients [5, 1]; however, the presence of heavy metals and a small percentage of bacteria compared to the overall flowrate of material, has the potential to limit end uses [5, 6]. 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 [7] and the Canadian Council of Ministers of the Environment (CCME) biosolids regulations [8, 9]. 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 sludge 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 [8, 9]. Ideally, pulp and paper sludge would meet Class A definition by Nova Scotia government regulations [8, 9]. Such regulations for land application (based upon municipal biosolids – more storage and/or capping focused) could be comparative for agricultural use [10]. 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 and/or incineration to manage the sludge produced at the facility. There are limited studies exploring the applicability of paper mill sludge for land-based soil amendment within the context of existing Canadian 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 in this study.

As an alternative to purchasing sod, hydroseeding is considered a cost-effective option for grass growth [11]. Hydroseeding is a commonly used process for seeding surfaces along road transportation corridors, 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 [12]. 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; [13]. 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 polymer has been utilized in combination with the cellulosic fiber in hydroseeding practices to aid in irrigation practices by reducing the requirement for regular water application, creating a hydrogel that holds water for use during the day or when water is scarce [12, 14].

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 [15]; 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. The overall objective of this study was to determine if pulp and paper sludge can replace the cellulosic additive utilized in hydroseeding applications. Specific objectives of the research were to identify the optimum sludge application rate, determine water retention and stability on incline planes, runoff properties and soil element bioaccumulation levels.

Materials and Methods

Three hydroseed growing sites in Nova Scotia, Canada were utilized for the study. The first site was a flat, open plain field on an industrial site located in Port Hawkesbury (45.5993° N, 61.3568° W) with two approximately 2.14 x 2.14 m^2 plots. This site was used for field trials that were run from June to August 2019. The second study site was operated on an approximately 0.4 m^2 outdoor slope (3:1 incline) with northwest facing sunlight located in Antigonish (~45.5993° N, 61.3568° W). This site was used for growth trials conducted in individual pans from August to September 2022. The third study site, also conducted with individual pans, was on an artificial 3:1 incline in a southwest facing greenhouse with natural lighting in Bible Hill, located specifically at the Dalhousie University Agricultural Campus, 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. Ambient field conditions during the period of the outdoor trials are provided in Appendix A.

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 and utilizes a thermomechanical (TMP) pulping process. The sludge from the mill contains waste from the papermaking process as well as the mill's sanitary sewer. The sludge samples were mixed on a mass percent basis with black earth (Greenhouse Gold, Envirem Organics Inc., New Brunswick, Canada) at varied percentages for the indoor and outdoor small scale growth trials (Table 1). All trial results were compared to a control mixture using 100% cellulosic additive (CA) (Celumulch, Thermo-Cell, Debert, Nova Scotia, Canada) that is comprised of 100% recycled newspaper with a temporary green dye additive.

Table 1 – Experimental masses of sludge (wet basis, 70% moisture content) and soil with 14 g embedded seed containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). In text mixtures are noted as S-SO with percentages representing sludge.

Mass Sludge (%)	Mass Soil (%)	Mass Sludge (g)	Mass Soil (g)	Mass Celumulch (g)
100	0	91.00	0.00	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	0.00	91.00	0
0 (control)	0	0.00	0.00	91.00

For the outdoor and greenhouse bench-scale studies with individual growth pans, a grass seed mix of Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra)*, Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*) (Home Gardener All-Purpose Premium Grass Seed, Speare Seeds Limited, Harriston, ON, Canada) was used. For the field studies where hydroseed was applied by a professional, third-party company, a mixture of 40% Creeping Red Fescue, 30% Perennial Ryegrass, and 30% Kentucky Bluegrass (Maritime Green Products, Sussex, New Brunswick, Canada) was used.

Bench-Scale Outdoor and Indoor Greenhouse Trials

Aluminum pans filled with a base layer of black earth (~2.5 cm thick) were topped with grass seed and sludge/black earth mixtures as presented in Table 1. The application rate of the overall mixture was approximately 5.65 kg/m^2 of fresh material based on recommended rates of application [13]. 105 g of fresh material (including embedded seed) was added to each pan and seeds were embedded (set mass/ volume of mixture). Compaction of the base layer of soil was completed manually with hand-applied pressure of approximately 0.7 kg/cm^2 [16] 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 bench-scale outdoor and greenhouse trial samples were watered daily with approximately 400 mL of tap water. The greenhouse 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 (indoor trial 1) and 13 days in IT2 (indoor trial 2).

Indoor and outdoor trials (IT and OT) were conducted twice with two replicates of varied/ extended growth durations of each mixture per trial. IT1 and IT2 were run for four and three weeks, respectively, while OT1 and OT2 were run for four and seven weeks.

Industrial Field Trial

The outdoor industrial field trial utilized a Hydro Seeder (FiNN T170 FiNN Corp., Fairfield, Ohio, United States) to spray test seed mixtures through a 5.08-cm diameter hose the cleared land space for the study. One half of the test site was sprayed with a conventional hydroseed mixture of seed (14 g), a cellulosic additive (73 kg), and water (1,886 kg or 1,892L). In the other section of the test site, the cellulosic additive was replaced with paper mill sludge (~118 kg) that was combined with seed (14 kg) and water (1,399 L) to achieve comparable consistency to the cellulosic additive mixture. The exact ratio was not determined as the adjustments were conducted in the field based on the experience of the hydroseeding technicians. An additional tackifier was not applied to either test section in the field study. The Application rates on the ground were kept consistent at ~5651.05 g/m^2 for both mixture test sites, 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.

Chemical Analysis

Complete metals (via EPA3050B, Acid Digestion of Sediments, Sludges, and Soils [17]) and *Escherichia 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 during the bench-scale outdoor and indoor greenhouse trials in August and September 2022. Samples of 1- 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 Nitrogen (N), Phosphorous (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), Manganese (Mn), Copper (Cu), Zinc (Zn), Boron (B) and Sodium (Na). These tests were conducted at the Nova Scotia Department of Agriculture Laboratory Services, Bible Hill, Nova Scotia.

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.

Growth Analysis

Qualitative and quantitative observations were undertaken for the bench-scale trials through blade counts, blade length measurements, germination rate and collection of runoff volumes for the indoor trials. For the field study, blade counts, and germination rates were determined. Blade counts were limited to 100 blades as beyond this point distinguishing between the blades in dense coverage became difficult and opened the potential for error. Blade lengths were measured pre-harvest (early August – end of September 2022) in bench-scale trials and approximately twice per week for the field site 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 [18]. 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 1) and then water was added to saturation and the remainder was decanted. This provides the ability of the base mixture to retain water.

Experimental Design and Statistical Analysis

Treatments were arranged in a randomized complete block design with three replications.

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.

Results and Discussion

Bench-Scale Outdoor and Indoor Greenhouse Trials

The progression of grass growth in the first trial of the indoor bench-scale greenhouse trials (IT1) is presented in Figure 1. The first trial (IT1) and the second (IT2) followed a similar pattern of grass growth, apart from the first evidence of germination in IT2 being one week behind IT1. Following one week of growth the growth media with 5 to 25% sludge were found to result in the quickest time to germination (Figure 1). 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.

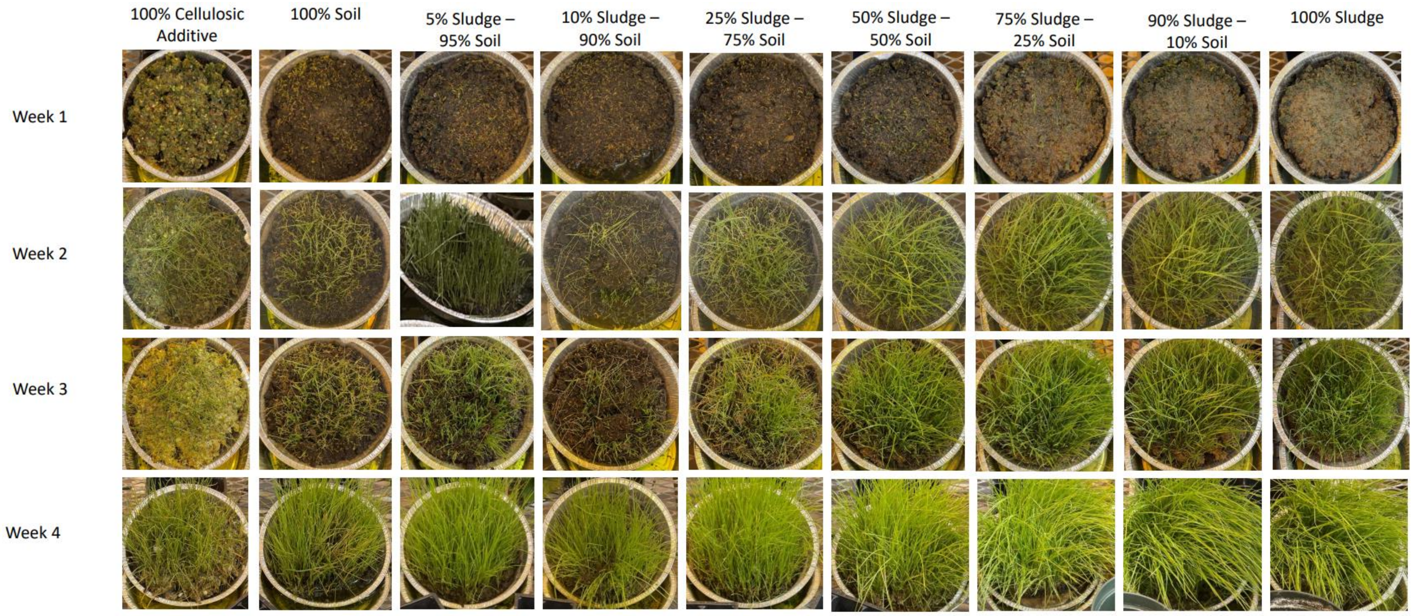

Fig. 1 – Indoor trial 1 (IT1) weekly grass growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

The sludge mixture was found to adhere well to the underlying soil mixture, except in the test pans containing the highest percentage of sludge (i.e., >50% sludge) 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.

The progression of grass growth in the second trial of the outdoor bench-scale trials (OT2) is presented in Figure 2. The first trial (OT1) and the second (OT2) followed a similar pattern of grass growth. The outdoor trials showed tremendous growth after the first week compared to the indoor trials, with the fastest, densest growth observed to have occurred in mixtures containing 10 to 25% sludge.

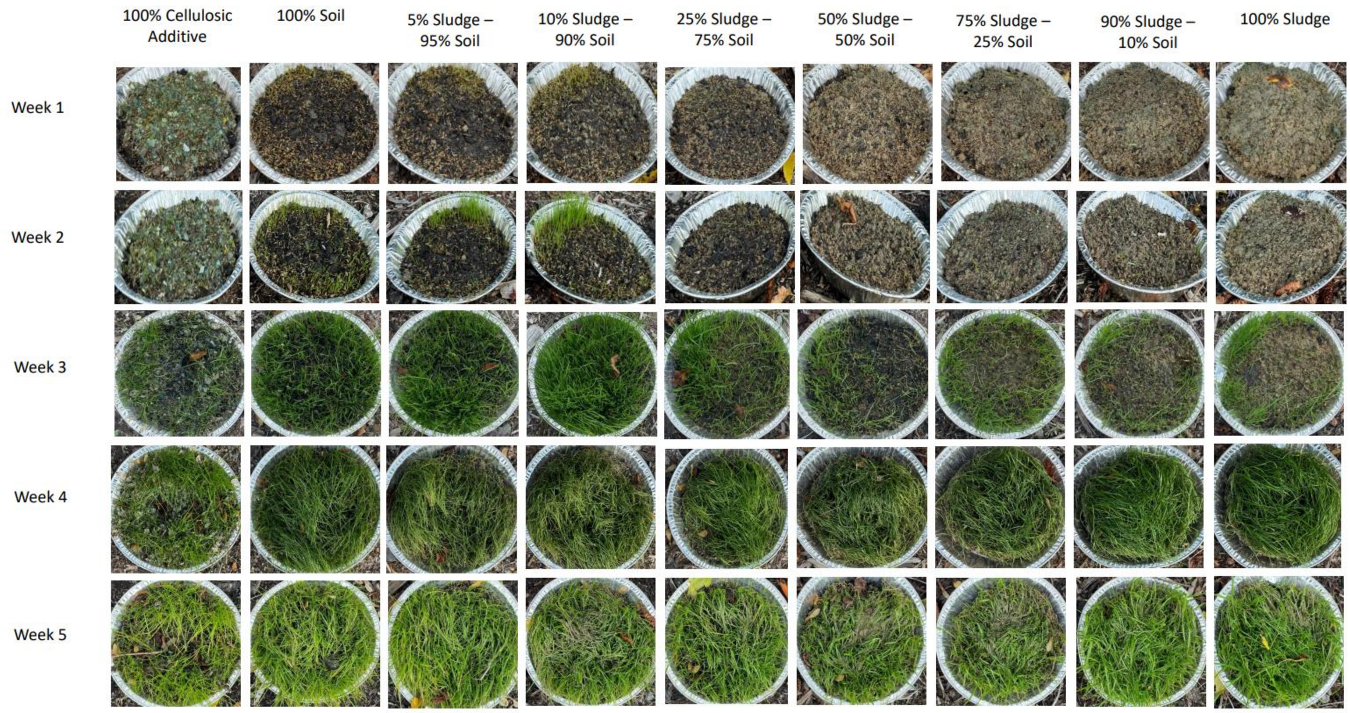

Fig. 2 – Outdoor trial 2 (OT2) weekly grass growth containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Treatments of 0-100% sludge were utilized.

As with the first indoor trial, the sludge-soil mixtures were found to adhere well to the soil base. Germination was seen two years post plant and over the duration of the trial the longest blade lengths were found in the 90 and 100% S-SO samples (Figure 3), while the densest coverage was found in 5-10% sludge. Compared to the CA sample, those containing low-mid percentages of sludge were competitive in both coverage/density and blade length. Compared to the indoor trials, germination was visible 1 week earlier. This could be related to further exposure to the environment (rain, etc.).

Figure 3 presents blade length measurements (blade length above soil level) over each week of growth, with averaged values from two replicates of varied/ extended growth durations of both the indoor and outdoor trials; specifically, points beyond 30 days post plant were collected in the outdoor trials and points prior from the indoor trial. 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.

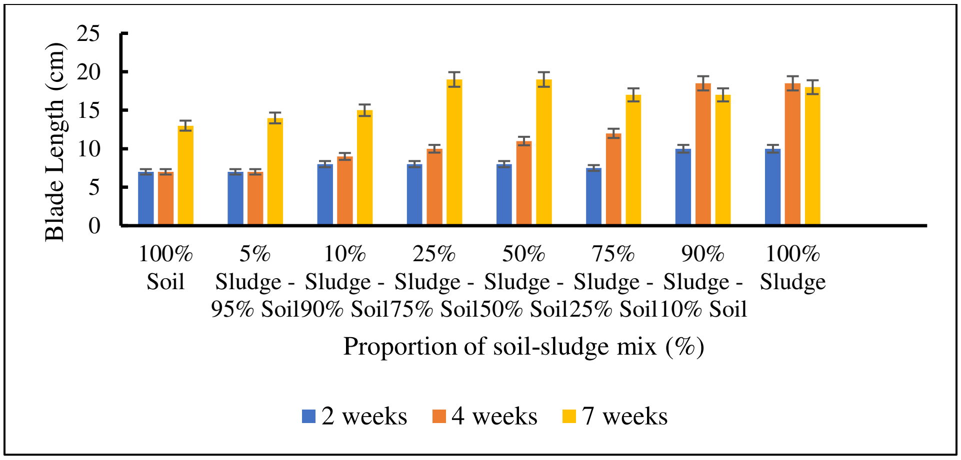

Fig 3 – Average blade length over varied amendment mixtures and weeks of testing of samples containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Vertical bars represent percentage standard error the mean (n=4).

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 with low-mid percentages of sludge reaching the 100-blade count quickest (typically within 2 weeks post plant). The data presented in Figure 4 illustrates that the 100% soil, 5,10, and 25% S-SO mixtures germinated the fastest (quickest appearance of growth) in both the indoor and outdoor trials. 4 weeks post plant, grass growth in all of the individual test pans looked similar, with those mixtures containing higher percentages of sludge producing noticeably longer blades of grass (5+ cm longer than low percentages). 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 of grass is inconsistent and not a statistically significant pattern.

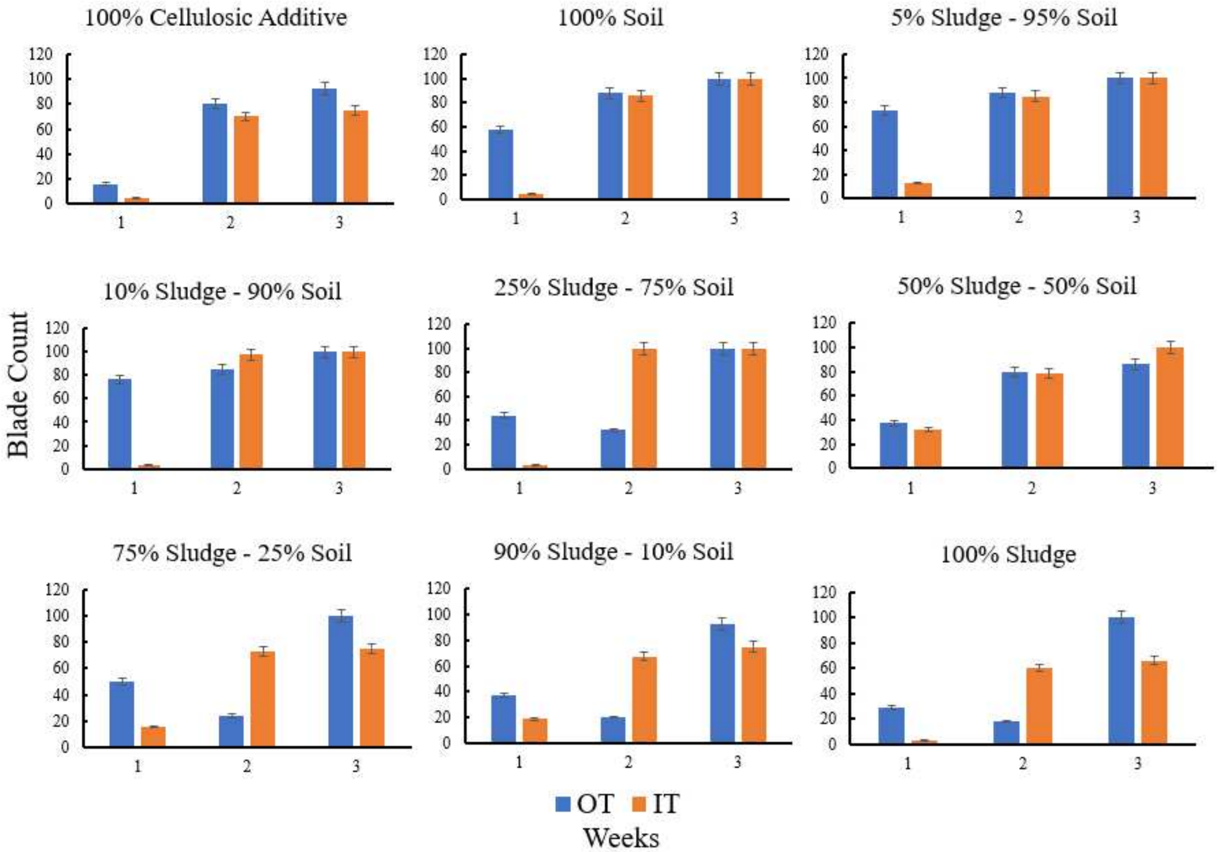

Fig. 4 – Average relative blade count for indoor and outdoor small-scale growth trials beginning 1 week post plant containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Error bars indicated in percentage.

Root-to-Shoot Ratios

Figure 5 presents the masses of grass, roots and root-to-shoot ratio (e.g., material above ground [18]) for all mixtures in IT. The data from this trial showed a decreasing trend in root-to-shoot ratio with increasing percentage of sludge in the growth media. The 5% sludge mixture sample was found to result in the highest root:shoot value. Root: shoot ratios were found to be directly relevant to the percentage of sludge within a mixture ($p < 0.05$). However, the direct relationship between percentage of sludge and grass or root mass was not found to be significant ($p > 0.05$).

As discussed previously, increasing sludge percentage in the growth media was also found to result in increasing blade length (i.e., shoot), which while aethetically pleasing, on an incline growth location, could prove detrimental without stable penetration of the roots into the soil base layer. Blade material collected was measured fresh, while root material was air-dried, creating potential inconsistencies in mass due to the presence of water in the fresh grass. However, the trends exhibited from both columns 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. The root: shoot ratio indicates that the strongest root base is found in 5% S-SO mixtures with the weakest root base being found in 100% S-SO.

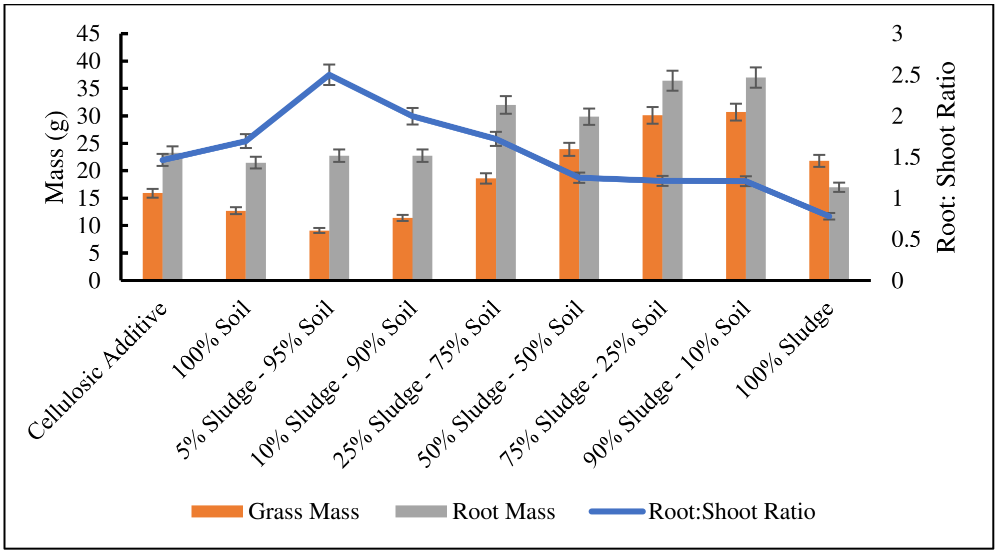

Fig. 5 – Root-to-shoot ratio for indoor grass trials (left vertical axis) versus grass and root mass (right vertical axis). Samples containing Kentucky Bluegrass (*Poa pratensis*), Creeping Red Fescue (*Festuca rubra*), Perennial and Annual Ryegrass (*Lolium perenne* and *Lolium multiflorum*). Imprecision Uncertainties u (root mass) = ±1 g. Error bars indicated in percentage. N = 3.

Industrial Field Trials

Following hydroseeding, photographs of the growth plots used in the field trial are presented in Figure 6 (after 12 days), and a close-up of the area near the center of each plot after 25 days (Figure 7). The dark area on the cellulose additive (CA) plot is from dye added in the CA mixture. No maintenance was provided to either test location following hydroseed application.

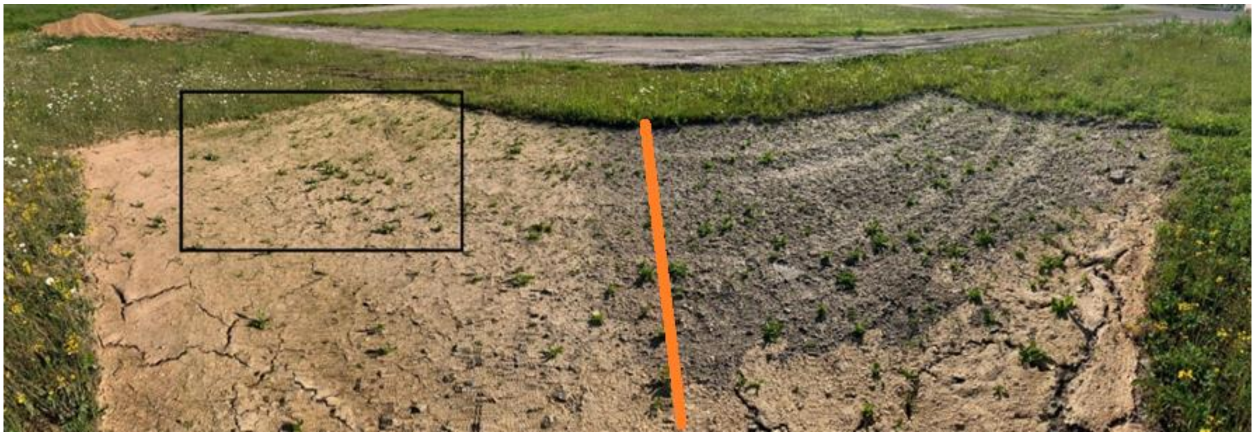

Fig. 6 - Panoramic view of 15 x 7 ft study area with orange line dividing sludge test side using 100% sludge with embedded seed (left) and Celumulch test side (right) using 100% Celumulch and embedded seed after 12 days. Both sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

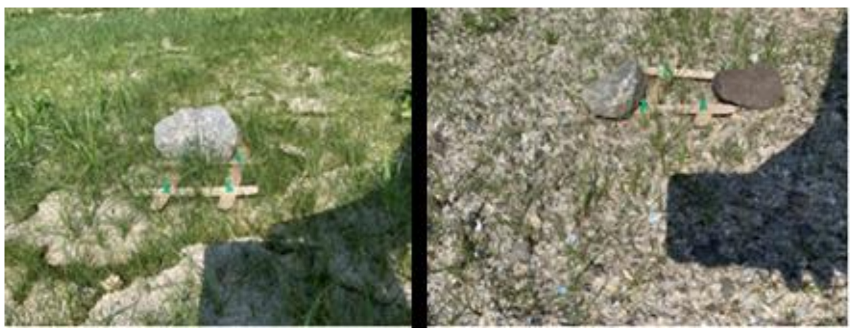

Fig. 7 – Grass follicles present 25 days post hydroseed application: left representing the sludge test side and right representing the Celumulch test side. Both contain embedded seed with 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

During the trial, blade count measurements were conducted within marked grid areas (Figure 9). Figure 8 presents 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 than the CA test side. 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 7), over the 25-day test period of this study. The growth site with the sludge showed significantly higher ($p < 0.05$) blade counts than the test site with the cellulose additive.

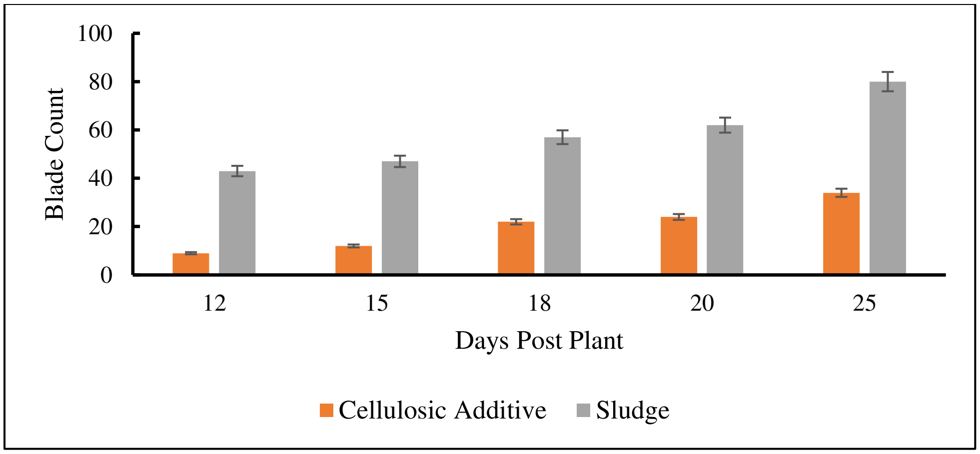

Fig. 8 – Blade count data for Celumulch based hydroseed mixture versus sludge hydroseed mixture ($p > 0.05$). Both sides contained grass growth composed of 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*). Error bars indicated 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 from Figures 1 and 2. Specifically, density of growth increased over the duration of both trials.

Elemental Analysis

Table 3 presents government regulations for biosolids land application compared to analyte values from study samples to determine if sludge-soil mixtures abide in various concentrations. The data indicates the potential for the sludge evaluated in this study to be utilized as a biosolids fertilizer. Given that the metal concentrations measured in the mixtures containing 100% CA, soil, and sludgeare all below Class A and B regulations, the risk of bioaccumulation of heavy metals is negligible. Data indicates the 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 [19] this further supports reduced concern for bioaccumulation.

Table 3 - 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	100% Sludge (base mixture) (mg/kg)	100% Cellulosic Additive (mg/kg)	100% Soil (mg/kg)	CCME Compost & NS	CCME Compost & NS

	*2015 basis (mg/kg)				Biosolids Class A (MAX) (mg/kg)	Biosolids Class B (MAX) (mg/kg)
Arsenic	-	<1.00	0.05 - 0.07	0.02 - 0.11	12	75
Cadmium	-	0.120	0.006 - 0.025	0.005 - 0.027	3	20
Chromium	3.0	4.0	<0.2 - 0.4	<0.2	210	1060
Cobalt	-	0.20	0.04 - 0.11	0.02 - 0.06	34	150
Copper	3.0	5.0	1.3 - 5.2	1.3 - 1.8	400	760
Lead	0.70	1.20	0.05 - 0.39	<0.02 - 0.1	150	500
Molybdenum	-	1.00	0.12 - 0.31	0.13 - 0.42	5	20
Nickel	-	<1.0	0.3 - 0.4	<0.2 - 0.5	62	180
Selenium	0.0	<1.0	<0.2	<0.2	2	14
Zinc	18.0	12.0	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 [19]. 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 [20] and conducive to ideal growth conditions but does not compete nutrient-wise with sludge-based mixtures.

Throughout the 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 [18, 21, 22]. 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. The paper mill sludge used in this study was found in previous studies [2, 20] to have tightly bound water molecules which required rupturing through the addition of acid via direct injection acidification [2]. 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 (TF) 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 [23]. Yan *et al*. [23] 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 [24]. The work conducted by Yan *et al*., [23] 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 4 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 [23] 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 3) 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 4 – 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

[1]IT represents indoor trials, OT represents outdoor trials, and TF represents transfer factors.

Seasonal Considerations

A series of samples were tested with results presented in Figure 10. 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 [2]. 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 10, all metal levels across seasons lie below those of the recent 2022 study, indicating no concern for use in hydroseeding applications with material from this study. 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.

1

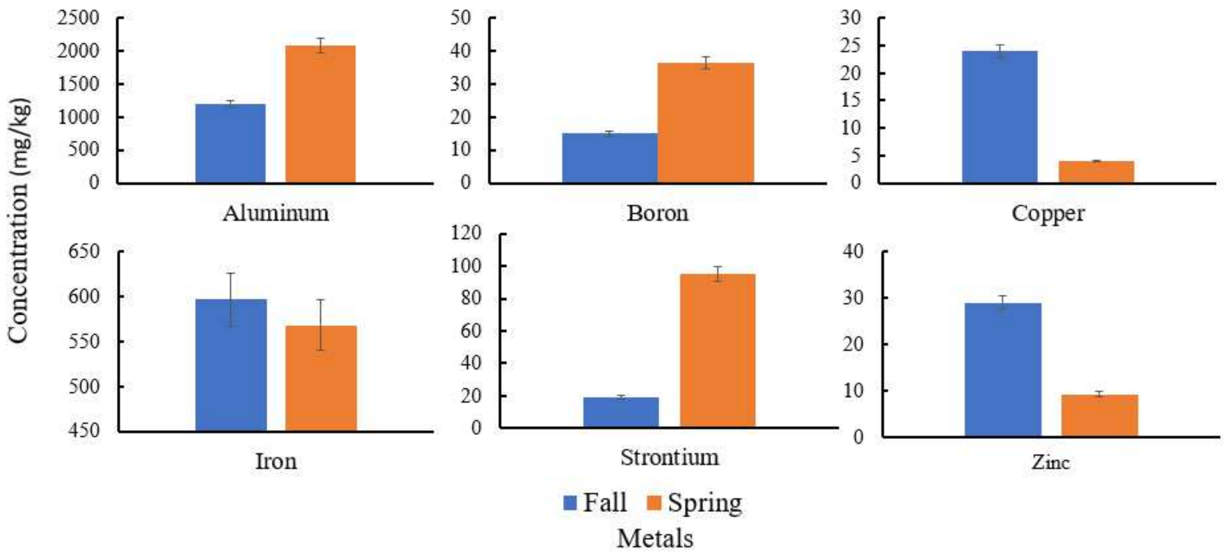

Fig. 10 – Seasonal metals comparisons for Port Hawkesbury Paper's sludge product. Error bars indicated in percentage.

Run-off analysis

Runoff volumes measured during the IT1 and IT2 trials are presented in Figure 11. Amounts in Figure 11 on average are greater in IT1; this appears to relate to either absorption and retention of water in mixtures or degradation of cellulosic material as runoff was collected at the completion of the trial, which would reduce available matter for water absorption. With p values greater than 0.05, differences in runoff volumes between IT1 and IT2 were not significant. 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.

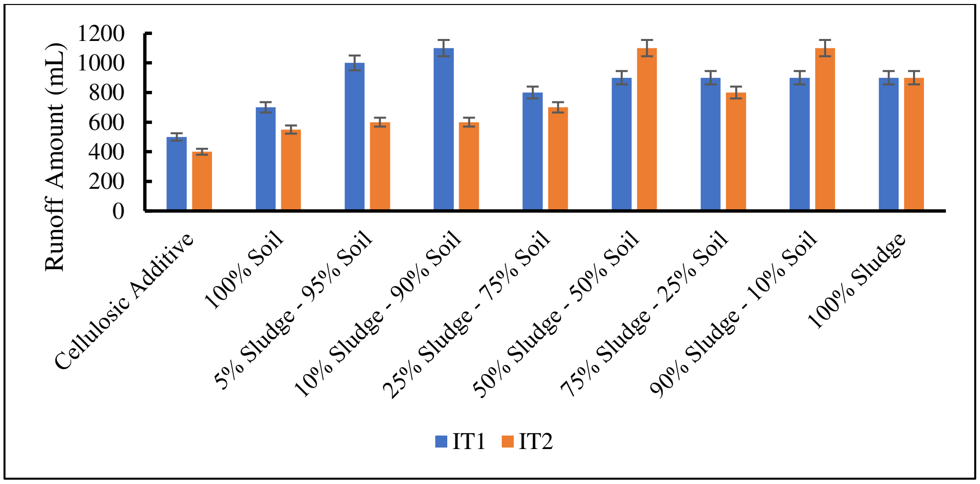

Fig. 11 - Runoff volumes over varied amendment compositions from a single 1000mL watering. Error bars indicated in percentage ($p < 0.05$). Samples contain seed with 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

Figure 12 presents information on water retention qualities of the sample 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.

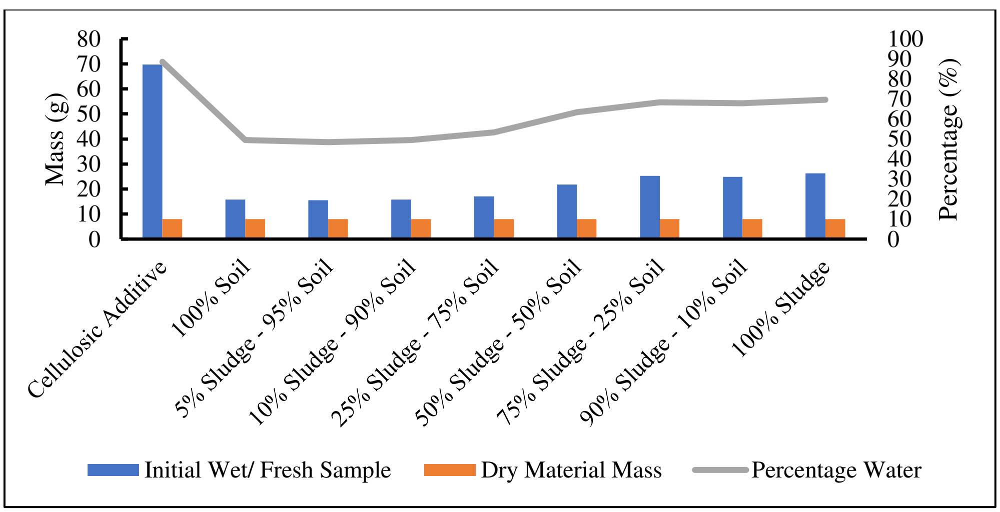

Fig. 12 – Ability of mixtures to retain water following saturation ($p > 0.05$). Samples contain seed with 40% Creeping Red Fescue (*Festuca rubra*), 30% Perennial Ryegrass (*Lolium perenne*), and 30% Kentucky Bluegrass (*Poa pratensis*).

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.

Conclusions

The results of this study have shown that pulp and paper mill sludge has the potential to act as an effective replacement for the cellulosic additive in hydroseeding applications. Results of field and bench-scale experiments have shown that although 100% sludge can fully replace any supplementary soil material, full consideration of the qualitative and quantitative data collected in this study suggest that mixtures of soil with 5 to 75% sludge would be most competitive and comparable to current outcomes using a CA after three weeks of growth. Growth media mixtures containing 5 to 25% sludge were shown to result in the quickest grass seed germination. When placed on an incline plane the effects of washaway were minimal suggesting that sludge does aid in supporting deep root breach. The initial concern of presence of heavy metals in the case study industry's sludge proved non-problematic in this study, 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. It is recommended that additional testing take place further investigate tackifying qualities.

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.

References

1. Faubert P, Barnabé S, Bouchard S, et al (2016) Pulp and Paper Mill Sludge Management Practices: What are the challenges to assess the impacts on greenhouse gas emissions? Resources, Conservation and Recycling 108:107–133. doi: 10.1016/j.resconrec.2016.01.007
2. MacDonald BA, Oakes KD, Adams M (2018) Molecular disruption through acid injection into waste activated sludge – a feasibility study to improve the economics of sludge dewatering. Journal of Cleaner Production 176:966–975. doi: 10.1016/j.jclepro.2017.12.014
3. O'Brien TA, Herbert SJ, Barker AV (2002) Growth of corn in varying mixtures of paper mill sludge and Soil. Communications in Soil Science and Plant Analysis 33:635–646. doi: 10.1081/css-120002769
4. Chong C, Purvis P (2004) Nursery crop response to substrates amended with raw paper mill sludge, composted paper mill sludge and composted municipal waste. Canadian Journal of Plant Science 84:1127–1134. doi: 10.4141/p04-031

5. Camberato JJ, Gagnon B, Angers DA, et al (2006) Pulp and paper mill by-products as soil amendments and plant nutrient sources. Canadian Journal of Soil Science 86:641–653. doi: 10.4141/s05-120
6. Anderson, R. (2015). (rep.). Opportunities for Beneficial Reuse of Port Hawkesbury Paper Residuals.
7. Government of Canada. (2020). *Fertilizers Act R.S.C., 1985, c. F-10*. Government of Canada.
8. Canadian Council of Ministers of the Environment (2005) Guidelines for Compost Quality.
9. Canadian Council of Ministers of the Environment (2019) Soil Quality Guidelines for the Protection of Environmental and Human Health.
10. Department of Environment, Halifax, N.S. (2010). Guidelines for Land Application and Storage of Municipal Biosolids in Nova Scotia
11. (1989) Starting from scratch: sod vs. seed. Southern Living 24:24s.
12. Parsakhoo A, Jajouzadeh M, Rezaee Motlagh A (2018) Effect of hydroseeding on grass yield and water use efficiency on forest road artificial soil slopes. Journal of Forest Science 64:157–163. doi: 10.17221/2/2018-jfs
13. Wisniewski N (2022) In the mix: Hydroseeding. In: Lawn & Landscape. https://www.lawnandlandscape.com/article/in-the-mix--hydroseeding--w--exclusive-online-copy-/. Accessed 5 November 2022
14. Ostrand MS, DeSutter TM, Daigh AL, et al (2020) Superabsorbent polymer characteristics, properties, and applications. Agrosystems, Geosciences & Environment. doi: 10.1002/agg2.20074
15. Dalzell CG (2021) Purpose-Grown Biomass Crops: Efficient Production and Real-world Verification. Thesis
16. Lee, Choi, J.-W., & Kim, H. (2007). Determination of Hand Surface Area by Sex and Body Shape using Alginate. Journal of Physiological Anthropology, 26(4), 475–483. https://doi.org/10.2114/jpa2.26.475
17. U.S. EPA. 1996. “Method 3050B: Acid Digestion of Sediments, Sludges, and Soils,” Revision 2. Washington, DC.
18. Mokany K, Raison RJ, Prokushkin AS (2005) Critical analysis of root: Shoot ratios in terrestrial biomes. Global Change Biology 12:84–96. doi: 10.1111/j.1365-2486.2005.001043.x
19. Ward PL, Wohlt JE, Zajac PK, Cooper KR (2000) Chemical and physical properties of processed newspaper compared to wheat straw and wood shavings as animal bedding. Journal of Dairy Science 83:359–367. doi: 10.3168/jds.s0022-0302(00)74887-9
20. MacDonald BA (2017) Dewatering strategies and end use examination of Paper Mill Residuals. Thesis
21. Ball BC, McTaggart IP, Scott A (2004) Mitigation of greenhouse gas emissions from soil under silage production by use of organic manures or slow-release fertilizer. Soil Use and Management 20:287–295. doi: 10.1079/sum2004257
22. Liu G, Zotarelli L, Li Y, et al (2014) Controlled-release and slow-release fertilizers as Nutrient Management Tools. EDIS. doi: 10.32473/edis-hs1255-2014
23. Yan X, Zhang F, Zeng C, et al (2012) Relationship between heavy metal concentrations in soils and grasses of roadside farmland in Nepal. International Journal of Environmental Research and Public Health 9:3209–3226. doi: 10.3390/ijerph9093209
24. Mackin HC, Shek KL, Thornton TE, et al (2021) The ‘Black Box’ of Plant Demography: How do seed type, climate and seed fungal communities affect grass seed germination? New Phytologist 231:2319–2332. doi: 10.1111/nph.17532

Statements and Declarations

We would like to recognize the support from a Mitacs Accelerate Grant – IT32158 - Paper mill biosolids reuse through integration into hydroseed mixtures.

Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available due to do volume of the data but are available from the corresponding author on reasonable request.

Appendix A

Environmental Conditions

Abiotic conditions were considered for all 3 trials, were considered and are presented in Figures 13-16. These graphs feature weather data from stations nearby to the site. Figures 13-14 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.

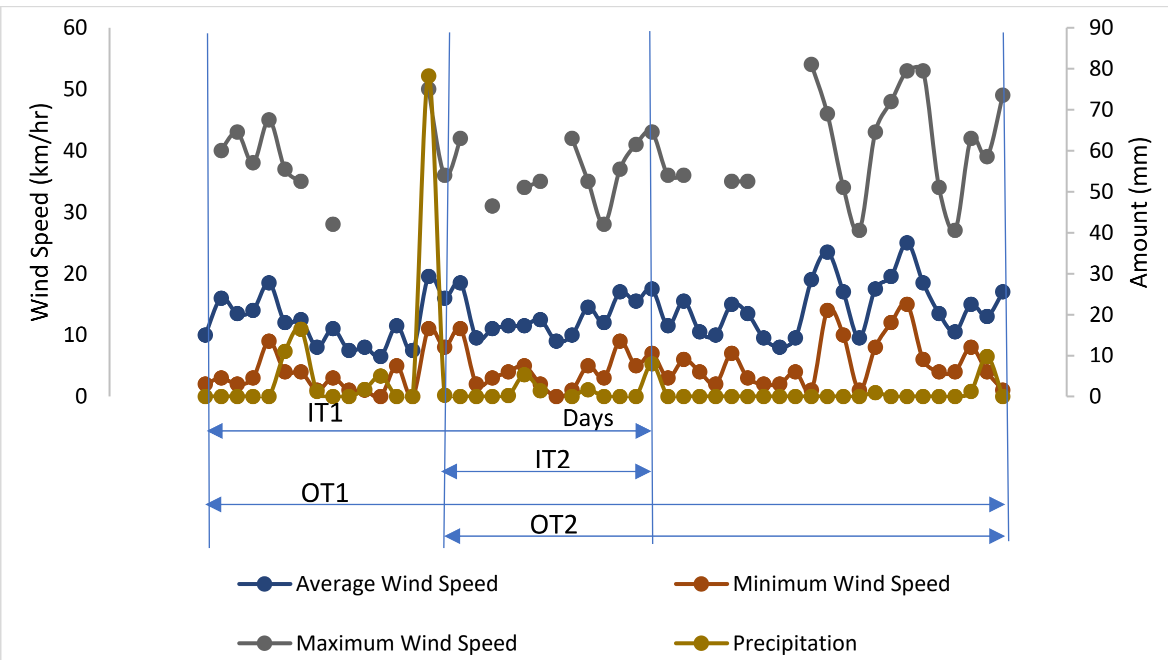

Fig. 13 - Antigonish weather data (wind and precipitation) for outdoor trials (compiled from Tracadie, Nova Scotia weather station (Latitude: 45.61, Longitude: -61.68, Elevation: 67 m) via weatherstats.ca.

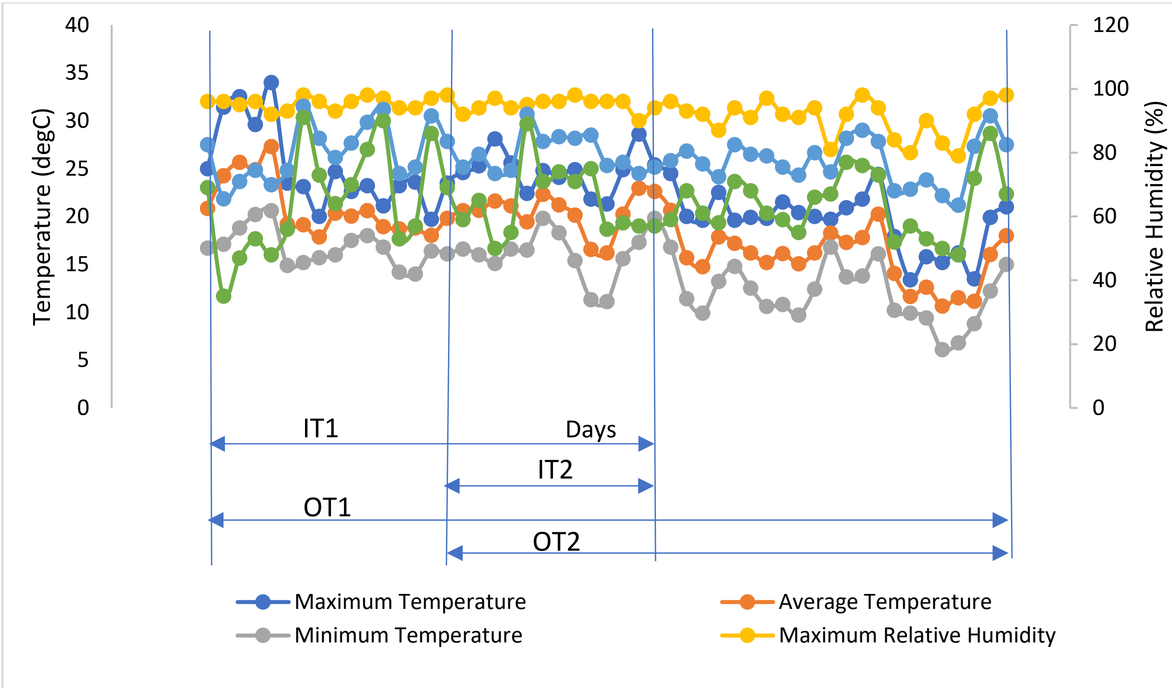

Fig. 14 - Antigonish weather data (temperature and humidity) for outdoor trials (compiled from Tracadie, Nova Scotia weather station (Latitude: 45.61, Longitude: -61.68, Elevation: 67 m) via weatherstats.ca.

Figures 15-16 provide weather data for the industry, land-based trials, taking place on a flat laydown area on the case study industry, PHP's site.

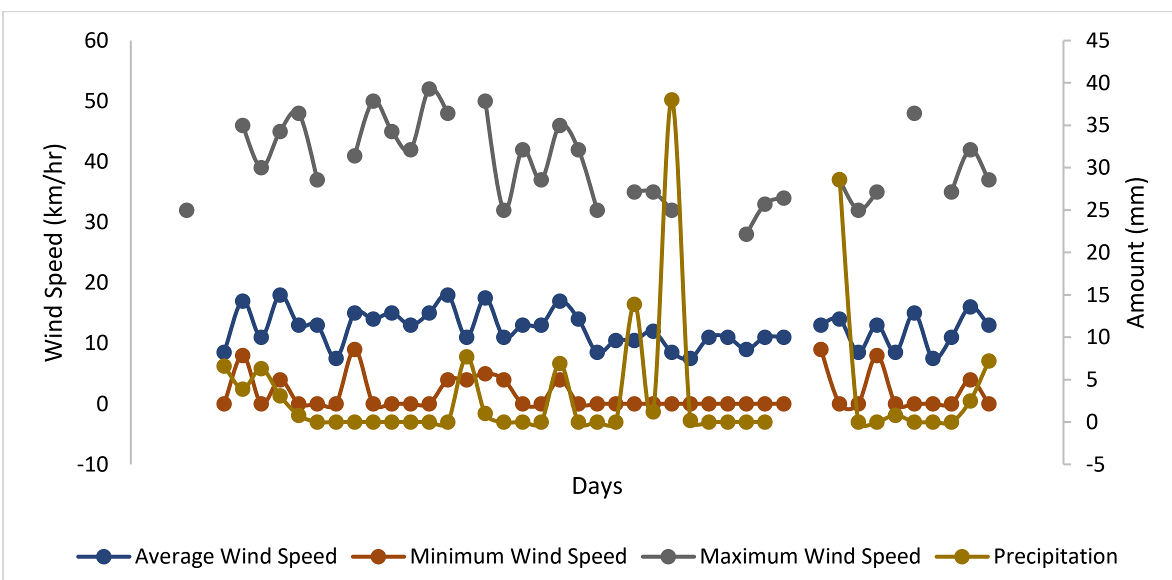

Fig. 15 – Port Hawkesbury weather data (wind and precipitation) for outdoor trials (compiled from Port Hawkesbury, Nova Scotia weather station (Latitude: 45.62, Longitude: -61.36) via weatherstats.ca.

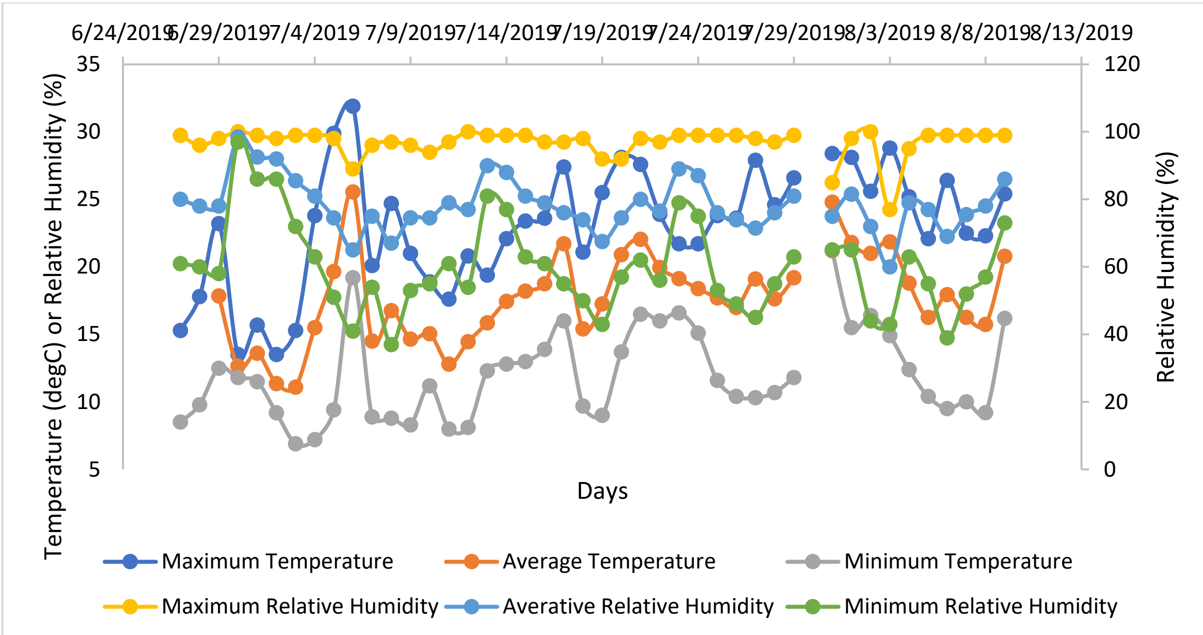

Fig. 16 – Port Hawkesbury weather data (temperature and humidity) for outdoor trials (compiled from Port Hawkesbury, Nova Scotia weather station (Latitude: 45.62, Longitude: -61.36) via weatherstats.ca.