

## Article

# Growth of Common Plants of Boreal Reclamation Sites in Oil Sands Tailings Cake Mixes and Process Water

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**Abstract:** Oil sands surface mining and processing in Alberta generate large volumes of fluid tailings and process water high in salts and metals, which must be reclaimed. We investigated growth of four common plants (two native and two non-native) found in boreal oil sands reclamation sites as influenced by substrate type (tailings cake, and mixtures of cake-sand, cake-peat, and cake-forest floor mineral mix) and water quality (0%, 50%, and 100% oil sands process water). Overall, cake-peat supported the highest aboveground biomass among substrates whereas cake and cake-sand performed poorly, possibly due to high sodium and chloride concentrations. Adding process water to substrates generally reduced growth or increased mortality. Grasses had greater growth than forbs, and for each functional group, non-native species performed better than native species. *Hordeum vulgare* had the highest overall growth with no mortality followed by *Agropyron trachycaulum* with negligible (0.5%) mortality. *Chamerion angustifolium* was most affected by the treatments with the lowest growth and highest mortality (56%). *Sonchus arvensis* had higher growth than *C. angustifolium* but its slow growth makes it less suitable for reclaiming tailings. Our results indicate that *H. vulgare* and *A. trachycaulum* could be good candidates for use in initial reclamation of oil sands tailings.

**Keywords:** boreal plants; forest land reclamation; oil sands; process water; tailings cake



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## 1. Introduction

The oil sands deposits in northern Alberta, Canada, represent the world's third largest oil deposit, with proven reserves of 165.4 billion barrels [1]. Oil sands surface mining results in severe forest disturbance. Following mine closure, disturbed lands are to be returned to an equivalent land capability, which can support land uses similar to the pre-disturbed land [2]. The Government of Alberta has also implemented a directive for progressive reclamation to ensure that all fluid tailings from a mining project are ready to reclaim ten years after the end of mine life [3].

The extraction process generates large volumes of fluid fine tailings comprised of connate and process water, sand, silt, clay, residual bitumen, inorganic salts, and organic compounds [4–6]. Process water is classified as free water, residing on top of the tailings material, or pore water, trapped within the fine spaces of tailings deposits. Oil sands fluid fine tailings is generally composed of 70–80% water, 20–30% solids, and 1–3% residual bitumen [5], and is alkaline and slightly brackish with high concentrations of organic acids [4]. The suspended solids in oil sands tailings are dominated by quartz and clays from the McMurray Formation, predominantly kaolinite, illite, and montmorillonite [7]. The total dissolved solids (TDS) in process water vary and change over time (for example, ranging from 600 to 2200 mg L<sup>−1</sup>) as TDS mostly depends on the type of ore being mined.

The aqueous cations are dominated by sodium while the anions are a mix of chloride, sulphate, and bicarbonate [8].

A variety of chemical, physical, and mechanical methods are used or are being tested to speed up the tailings dewatering process, with the objective of more quickly producing a solid deposit with sufficient strength for reclamation. One of the first commercially implemented tailings management method was composite or consolidated tailings where fine and coarse tailings are mixed along with sufficient gypsum to create a non-segregating solid mixture, which can settle to approximately 70 wt.% solids after one to two years. Another commercially used method is centrifugation in combination with chemical amendments to rapidly dewater tailings to produce tailings cake, with a typical solids content of 55 to 60 wt.%. In this study, we focus on tailings cake produced by centrifugation. As tailings are being reclaimed, it is important to understand the effects of dewatered tailings (as substrates) and process water (as groundwater seepage) on plant development and growth.

Response of plant growth to tailings or process water have been shown to vary depending on species. Above- and belowground biomass of one-month-old jack pine seedlings treated with process water was reduced by 31% and 20%, respectively, compared to seedlings irrigated with deionized water [9]. A positive correlation was also found between needle necrosis and tissue sodium and chloride for seven-month-old seedlings treated with process water [9]. Pouliot et al. [10], however, observed no stress signs after two growing seasons for fen vascular plants irrigated with process water, but groundwater discharge of process water adversely affected mosses under dry conditions. For raspberry grown in soil amended with 15% (by volume) fluid fine tailings, shoot and root dry weights reduced by more than 50%, but in conifer seedlings, shoot and root dry weights were not significantly different from those in control soils with no fluid fine tailings after 3 months [11]. Although plant responses to tailings or process water have been documented, it is unclear how the synergistic stress of tailings and process water may affect growth and development of common species in boreal reclamation sites. Knowledge of the combined effect of tailings and process water on plant growth will help identify species that would be suitable for consideration in reclaiming oil sands tailings.

A desirable goal for reclaimed land in the oil sands region in northern Alberta is to have a functioning forest ecosystem composed of native plant species. However, substantial changes in forest ecosystems due to mining activities, e.g., increased soil salinity [12], may hinder growth of native species and favor non-native ones. Mixing contaminated sediments with soil [13] or modifying the physiochemical environment of contaminated sites through the addition of organic matter and nutrients in addition to planting native species acclimated to contaminated soils [14,15] may reduce the concentration of contaminants such as excess salts and improve plant growth. There is limited literature on the effect of heavy metals from process water on boreal plant health. However, it is well known that some heavy metals can accumulate within plants at high concentrations without any indication of stress [16–18]. Increase in concentrations of these metals above plant threshold levels would modify plant physiological processes [19]. Consequences include visible changes in plant morphology, such as chlorosis and necrosis in leaves, stunted plant growth, and changes in root structure [19–22].

In the current study, we investigated the response of four native and non-native plant species commonly found in newly reclaimed areas in the boreal forest region of Canada: *Chamerion angustifolium* (L.) Holub (fireweed, native forb), *Sonchus arvensis* L. (perennial sow thistle, non-native forb), *Agropyron trachycaulum* (Link) Malte (slender wheatgrass, native grass), and *Hordeum vulgare* L. (barley, non-native grass). Our objectives were to determine the effect of oil sands tailings, mixtures of treated oil sands tailings and reclamation substrates, and oil sands process water on aboveground biomass and mortality of these four plants.

## 2. Materials and Methods

### 2.1. Experimental Set Up

This was a randomized, complete block design, greenhouse pot study with 4 species  $\times$  4 substrates  $\times$  3 water quality treatments  $\times$  6 blocks (gradient of sunlight and temperature within greenhouse as influenced by distance of pots to greenhouse window) for a total of 288 pots. Additionally, control pots with no plants were set up for each substrate  $\times$  water combination, with 6 replicates for each combination for a total of 72 control pots. The greenhouse temperature was set at 22–24 °C during the day (1000–2000 h) and 18–22 °C at night (0100–0600 h), relative humidity was set to 30% and 40% during the day and night, respectively, and an artificial light source (LumiGrow Pro 650) was turned on automatically, within a 16-h period (0500–2100), when natural light intensity fell below 200 W m<sup>-2</sup>.

### 2.2. Substrates and Process Water

We used four tailings substrates: (i) pure centrifuge tailings cake, and mixtures (1:1 by volume) of (ii) tailings cake and forest floor mineral mix (FFMM) (cake-FFMM), (iii) tailings cake and sphagnum peat moss (cake-peat), and (iv) tailings cake and sand (cake-sand).

The tailings cake was created by centrifuging a mixture of fluid fine tailings (obtained from an operational mine site in northern Alberta), gypsum (~900 ppm), and a high molecular weight anionic polymer, A3338 polymer (~1000 ppm). The resulting tailings cakes had 55.7 wt.% solids. The sand and sphagnum peat moss were commercially obtained, and FFMM was obtained from an operational mine site in northern Alberta and consisted of forest floor materials mixed with the underlying mineral soil.

Three types of irrigation water were used, which differed in quality: 0%, 50%, and 100% process water. The 0% process water consisted of reverse osmosis water whereas the 100% process water was the centrate water obtained from the centrifugation process used to produce the tailings cake. The 50% process water was made up of equal proportions of reverse osmosis water and 100% process water.

Chemical characterization of the substrates and process water used for the experiment (Table 1) was done by CanmetENERGY, Natural Resources Canada, Devon, AB, Canada. Tailings cake and tailings cake mixtures were slightly alkaline to alkaline (pH of 7.2–8.2). In general, concentrations of ions in the 100% process water were approximately double that of the 50% process water and were both substantially greater than the 0% process water. The 0% process water was slightly acidic (pH of 6.7) and the 50% and 100% process water were alkaline (pH of 8.2). To estimate soil nutrient supply rates during the period of the experiment, a pair of anion and cation plant root simulator (PRS; Western Ag Innovations, Saskatoon, SK, Canada) probes were installed to a depth of 9–10 cm in the control pots. PRS probes give estimates of soil nutrient supply rates by attracting and adsorbing ions on negatively and positively charged ion-exchange membranes [23,24]. The probes were removed after eight weeks, washed with reverse osmosis water and sent to Western Ag Innovations for extraction and laboratory analysis.

**Table 1.** Chemical characteristics of substrates and process water used for plant growth. EC, TDS, and SAR represent electrical conductivity, total dissolved solids and sodium adsorption ratio, respectively.

|                               | Substrate |                      |             |             | Water           |                   |                    |
|-------------------------------|-----------|----------------------|-------------|-------------|-----------------|-------------------|--------------------|
|                               | Cake      | Sand + Cake          | FFMM + Cake | Peat + Cake | Reverse Osmosis | 50% Process Water | 100% Process Water |
| Percent solids (%)            | 56        | 78                   | 73          | 53          |                 |                   |                    |
| pH                            | 7.90      | 8.21                 | 7.87        | 7.17        | 6.71            | 8.24              | 8.26               |
| EC (mS/cm)                    | 2.79      | 4.95                 | 4.73        | 2.39        | 0.02            | 1.16              | 2.18               |
| TDS Calculated (g/L)          | 3.69      | 5.64                 | 4.82        | 2.86        | 0.02            | 1.06              | 1.87               |
| SAR Concentrations            |           | mg/kg mineral solids |             |             |                 | mg/L              |                    |
| Na                            | 867       | 910                  | 754         | 559         | 4.1             | 285               | 495                |
| Cl <sup>-</sup>               | 215       | 212                  | 202         | 190         | 1.11            | 133.5             | 238                |
| CO <sub>3</sub> <sup>2-</sup> | 5.5       | 5.5                  | <3.8        | <3.8        | <3.8            | 5.9               | 13                 |
| HCO <sub>3</sub> <sup>-</sup> | 1266      | 1567                 | 1678        | 471         | 12.7            | 466               | 858                |

Table 1. Cont.

| Substrate                     |      |      |      |      | Water |      |      |
|-------------------------------|------|------|------|------|-------|------|------|
| SO <sub>4</sub> <sup>2−</sup> | 837  | 1766 | 1214 | 1017 | 2.30  | 94.9 | 151  |
| Ca                            | 85   | 368  | 294  | 86   | 0.33  | 11.4 | 21.4 |
| K                             | 42   | 56   | 78   | 44   | <0.01 | 7.73 | 13.1 |
| Mg                            | 35   | 97   | 116  | 53   | 0.37  | 7.73 | 12.4 |
| S                             | 319  | 614  | 435  | 383  | 0.88  | 36.5 | 58.9 |
| B                             | 5.49 | 6.67 | 6.16 | 6.27 | 0.14  | 0.81 | 1.34 |
| Ba                            | 0.96 | 0.83 | 0.71 | 8.21 | 0.00  | 0.22 | 0.39 |
| Al                            | 0.07 | 0.04 | 0.63 | 1.49 | 0.00  | 0.03 | 0.02 |

### 2.3. Plants

The species selected for this experiment were *Chamerion angustifolium* (L.) Holub (native forb), *Sonchus arvensis* L. (non-native forb), *Agropyron trachycaulum* (Link) Malte (native grass), and *Hordeum vulgare* L. (non-native grass). These are common plant species found in newly reclaimed areas or used as cover species in reclamation and are fast growing herbaceous species suitable for short-term greenhouse experiments. They are also representatives of both native and non-native grasses and forbs.

Seeds of *S. arvensis* were obtained from Canadian Natural Resources Limited (Fort McKay, AB) and seeds of the remaining species were obtained from commercial sources across Canada and the United States of America. The seeds were germinated under greenhouse conditions in styroblocks (plug size of 2.5 cm in diameter and 11.3 cm in length) using a commercial garden soil and watered as needed. Five average-sized seedlings of each species were transplanted into 1.5-L pots filled with the experimental substrates and allowed to settle for one week before watering with the process water. During this period, plants were manually watered to field capacity with greenhouse irrigation water and those that died were replaced. At the end of this period, three healthy plants were selected for the experiment, and the remaining plants were uprooted from the pots. The plants were then watered manually each day with the process water on an as needed basis.

We applied a 20-20-20 nitrogen, phosphorus, and potassium fertilizer at rates of 75 mL per week (recommended rates by manufacturers) for the first four weeks and 15 mL biweekly (equivalent to the rate used in reclamation practices, i.e., 100 kg nitrogen ha yr<sup>−1</sup>) for the last four weeks of the experiment. Fertilization is commonly used in oil sands reclamation in Alberta to ensure that planted or naturally regenerated plants have adequate nutrients for establishment and early growth [25].

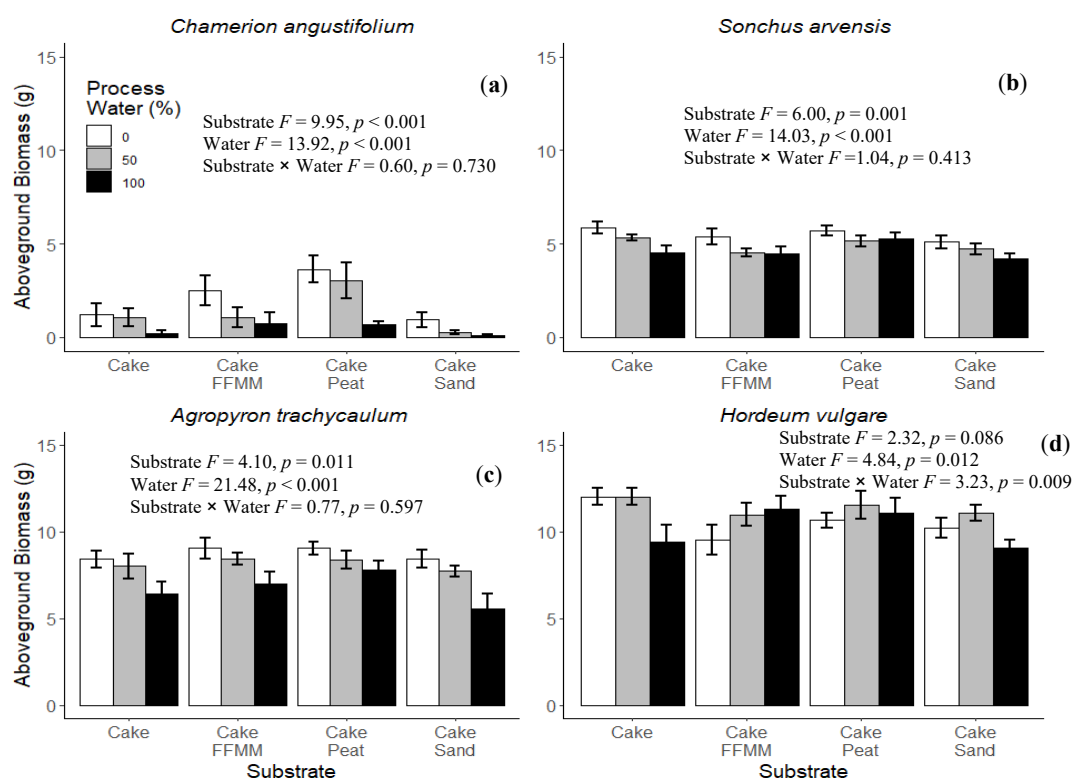
Plants were grown under the experimental conditions for eight weeks and mortality was recorded in the final week of the experiment. At the end of the 8-week period, plants were clipped at the soil surface and dried to a constant weight at 40 °C to obtain aboveground biomass.

### 2.4. Data Analysis

Mixed model analysis of variance (ANOVA), with block as the random factor, was used to test for differences in aboveground biomass and mortality among substrates and watering treatments for each species at the end of the study. Tukey's procedure was used for pairwise comparisons. Cube root transformation was applied to *C. angustifolium* aboveground biomass to meet ANOVA assumption of homoscedasticity. Differences in nutrient concentrations were also tested among substrates with one-way ANOVA. Correlation analyses (spearman rank correlation) were performed between nutrient supply rates from the control pot and aboveground biomass for each species. Mixed model ANOVA and multiple comparison tests were performed with nlme [26] and emmeans [27] packages, respectively. Correlation coefficients and associated probability values were calculated with psych package [28]. ANOVA and correlation analysis were performed with R statistical software [29], and statistical significance was considered at  $p < 0.05$ .

### 3. Results

Across all treatments, the grasses, *H. vulgare* (10.73 g) and *A. trachycaulum* (7.85 g), exhibited 2–8 times greater aboveground biomass than the forbs, *S. arvensis* (5.01 g) and *C. angustifolium* (1.28 g), and the introduced species performed better than the native species within each functional group (Figure 1a–d.) Among substrates, cake-peat supported the overall highest aboveground biomass (6.83 g), followed by cake-FFMM (6.24 g), cake (6.20 g), and cake-sand (5.61), and the 0% process water, overall, supported a higher aboveground biomass (6.72 g) than the 50% (6.45 g) and 100% (5.49 g) process water. There were varying responses of aboveground biomass to substrate and water treatments among the four species.



**Figure 1.** Total aboveground biomass (mean and standard error) of four understory species (a). *Chamerion angustifolium*; (b). *Sonchus arvensis*; (c). *Agropyron trachycaulum*; (d) *Hordeum vulgare*, commonly found in newly reclaimed areas in the boreal forest region of Canada, under four soil amendments and three watering treatments.

The treatment effects were most pronounced in *C. angustifolium* (Figure 1a), with cake supporting 67% lower aboveground biomass than cake-peat ( $p < 0.001$ ), and cake-sand supporting 70% or 82% lower aboveground biomass than cake mixed with FFMM ( $p = 0.035$ ) or peat ( $p < 0.001$ ), respectively. For the same species, watering with 100% process water reduced aboveground biomass by 79% ( $p < 0.001$ ) and 68% ( $p = 0.007$ ) compared to watering with 0% and 50% process water, respectively. For *S. arvensis*, cake-sand supported 13% and 11% lower biomass than cake-peat ( $p = 0.004$ ) and cake ( $p = 0.030$ ), respectively, and cake-FFMM supported 11% lower biomass than cake-peat ( $p = 0.021$ ). Watering with 100% and 50% process water also reduced aboveground biomass by 16% ( $p < 0.001$ ) and 10% ( $p = 0.003$ ), respectively, compared to watering *S. arvensis* with 0% process water (Figure 1b). Differences in aboveground biomass among substrates was only found between cake-peat (8.40 g) and cake-sand (7.24 g) ( $p = 0.013$ ) for *A. trachycaulum*, and for the same species, watering with 100% process water reduced aboveground biomass by 23% ( $p < 0.001$ ) and 18% ( $p = 0.005$ ) compared to watering with 0% and 50% process water, respectively (Figure 1c). Substrate  $\times$  process water interaction effect on variation in aboveground biomass was only observed for *H. vulgare*. Cake-sand watered with 100%



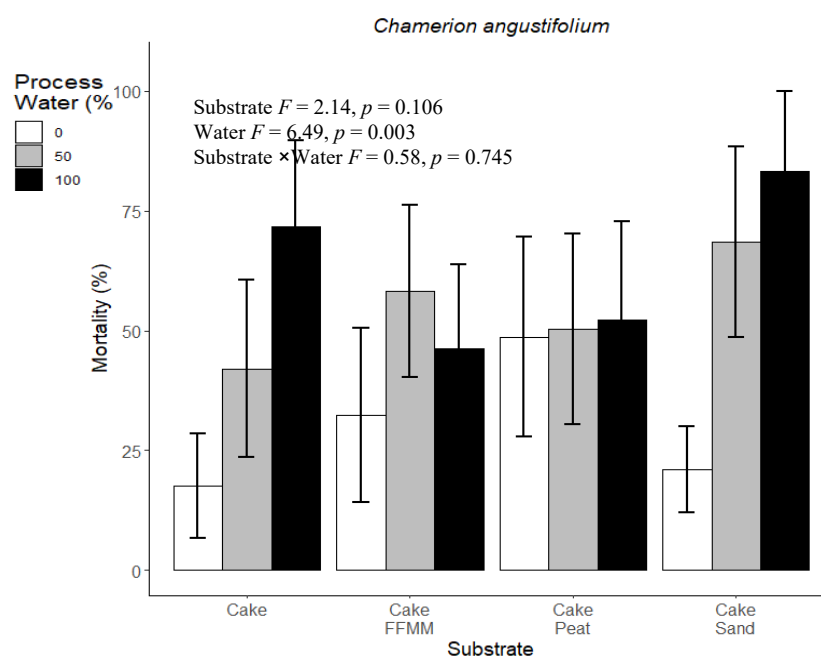
process water had 25% or 26% lower aboveground biomass than cake watered with 50% ( $p = 0.023$ ) or 0% ( $p = 0.020$ ) process water (Figure 1d).

In relation to supply rates of nutrients (Table 2), *C. angustifolium* aboveground biomass was positively correlated with nitrate ( $p = 0.030$ ), phosphorus ( $p = 0.040$ ), and magnesium ( $p = 0.010$ ), and *S. arvensis* was positively correlated with magnesium ( $p = 0.040$ ). No significant relationships were found between the other species and nutrients supply rates (Table 2).

**Table 2.** Spearman rank correlations between plant aboveground biomass and nutrient supply rates across substrates and watering treatments. Statistically significant correlations are marked with asterisk.

| Species                        | NH <sub>4</sub> <sup>+</sup> | NO <sub>3</sub> <sup>−</sup> | P      | K    | Ca    | S     | Mg     |
|--------------------------------|------------------------------|------------------------------|--------|------|-------|-------|--------|
| <i>Chamerion angustifolium</i> | 0.56                         | 0.64 *                       | 0.61 * | 0.30 | 0.13  | −0.10 | 0.75 * |
| <i>Sonchus arvensis</i>        | 0.55                         | 0.20                         | 0.49   | 0.34 | −0.13 | −0.13 | 0.61 * |
| <i>Agropyron trachycaulum</i>  | 0.29                         | 0.53                         | 0.57   | 0.00 | 0.38  | 0.13  | 0.52   |
| <i>Hordeum vulgare</i>         | 0.34                         | 0.15                         | 0.44   | 0.42 | −0.34 | −0.31 | 0.34   |

Mortality was only observed among the native species. *C. angustifolium* had the highest mortality across treatments (56%), followed by a negligible amount for *A. trachycaulum* (0.5%) (Figure 2). For *C. angustifolium*, 100% and 50% process water had 36% ( $p = 0.004$ ) and 29% ( $p = 0.022$ ), respectively, higher mortality than 0% process water, but neither substrate nor substrate  $\times$  water interaction effect was significant.



**Figure 2.** Mortality (mean and standard error) for *Chamerion angustifolium* under four soil amendments and three watering treatments.

Mixing cake with peat substantially reduced concentrations of sodium, chloride, and the carbonate, HCO<sub>3</sub><sup>−</sup>, from 867 mg kg<sup>−1</sup>, 215 mg kg<sup>−1</sup>, and 1266 mg kg<sup>−1</sup>, respectively, to 559 mg kg<sup>−1</sup> ( $p = 0.003$ ), 190 mg kg<sup>−1</sup> ( $p = 0.033$ ), and 471 mg kg<sup>−1</sup> ( $p < 0.001$ ), respectively (Table 1). On the other hand, electrical conductivities and concentrations of macronutrients (calcium, potassium, magnesium, and sulfur) tended to increase when cake was mixed with sand or FFMM but not with peat (Table 1). Supply rates of nitrogen, phosphorus, and potassium were generally lower for cake-sand compared to that of the other substrates (Table 3).

**Table 3.** Mean values (associated standard errors) of supply rates of nutrients over an 8-week period for tailings cake and cake-amendments under three watering treatments.

| Substrate   | Process Water (%) | Nutrient Supply Rate ( $\mu\text{g } 10 \text{ cm}^{-2} \text{ 8 Weeks}^{-1}$ ) |                 |              |               |                   |                 |                 |
|-------------|-------------------|---|-----------------|--------------|---------------|-------------------|-----------------|-----------------|
|             |                   | $\text{NH}_4^+$   | $\text{NO}_3^-$ | P            | K             | Ca                | S               | Mg              |
| Cake        | 0                 | 8.2<br>(2.6)  | 0.0<br>(0.0)    | 7.4<br>(2.5) | 44.9<br>(3.2) | 1700.6<br>(51.9)  | 270.3<br>(54.3) | 505.2<br>(25.1) |
| Cake        | 50                | 6.0<br>(1.3)  | 0.0<br>(0.0)    | 3.0<br>(0.9) | 47.3<br>(3.2) | 1592.4<br>(84.3)  | 238.2<br>(39.6) | 490.5<br>(24.3) |
| Cake        | 100               | 6.3<br>(1.8)  | 0.0<br>(0.0)    | 1.3<br>(0.3) | 45.7<br>(3.2) | 1444.2<br>(43.90) | 266.8<br>(66.1) | 469.3<br>(21.8) |
| Cake + FFMM | 0                 | 4.6<br>(1.6)  | 2.8<br>(2.8)    | 5.5<br>(0.7) | 30.4<br>(1.1) | 2144.3<br>(71.0)  | 315.8<br>(56.2) | 530.0<br>(22.0) |
| Cake + FFMM | 50                | 5.2<br>(2.0)  | 2.6<br>(1.8)    | 3.7<br>(0.7) | 32.5<br>(1.7) | 2025.5<br>(84.1)  | 302.7<br>(24.0) | 508.6<br>(19.2) |
| Cake + FFMM | 100               | 3.09<br>(0.9)   | 5.7<br>(3.9)    | 3.9<br>(0.3) | 32.0<br>(1.7) | 1997.4<br>(111.9) | 336.0<br>(58.0) | 479.0<br>(18.0) |
| Cake + Peat | 0                 | 19.8<br>(3.0)   | 0.2<br>(0.2)    | 2.1<br>(0.4) | 49.6<br>(2.3) | 1845.5<br>(59.8)  | 638.4<br>(82.6) | 569.8<br>(17.5) |
| Cake + Peat | 50                | 16.3<br>(2.9)   | 0.07<br>(0.1)   | 2.0<br>(0.1) | 51.8<br>(2.2) | 1742.3<br>(46.7)  | 500.4<br>(65.9) | 540.2<br>(12.0) |
| Cake + Peat | 100               | 12.9<br>(3.6)   | 0.0<br>(0.0)    | 2.0<br>(0.4) | 53.0<br>(2.3) | 1659.2<br>(86.2)  | 599.3<br>(51.5) | 530.3<br>(17.0) |
| Cake + Sand | 0                 | 2.4<br>(0.3)  | 0.0<br>(0.0)    | 2.2<br>(0.3) | 27.1<br>(1.4) | 2117.6<br>(62.7)  | 875.8<br>(80.4) | 379.2<br>(16.7) |
| Cake + Sand | 50                | 2.0<br>(0.4)  | 0.00<br>(0.0)   | 1.3<br>(0.1) | 29.9<br>(2.1) | 2083.4<br>(109.3) | 723.6<br>(28.0) | 395.7<br>(23.7) |
| Cake + Sand | 100               | 2.5<br>(0.8)  | 0.0<br>(0.0)    | 1.0<br>(0.1) | 30.8<br>(1.5) | 1990.2<br>(86.4)  | 615.7<br>(45.5) | 382.8<br>(10.0) |

#### 4. Discussion

We examined the effect of oil sands tailings, mixtures of treated oil sands tailings and reclamation substrates, and oil sands process water on aboveground biomass and mortality of four plants (*C. angustifolium*, *S. arvensis*, *A. trachycaulum* and *H. vulgare*) commonly found in boreal oil sands reclamation sites. Overall, cake-peat supported the highest aboveground biomass among substrates whereas cake and cake-sand performed poorly. Another study also reported that consolidated tailings amended with peat improved germination, survival, and growth compared to plants growing directly in consolidated tailings [30]. In the present study, mixing cake with peat reduced pH and substantially reduced the concentrations of sodium, chloride, and carbonates. The high pH of tailings could result in plant mineral deficiency by reducing available macronutrients (e.g., phosphorus and nitrogen) and trace elements [30]. Salts are also known to adversely affect plant water balances by targeting the osmotic gradient across cells [31,32]. In particular, chloride has been observed to accumulate in shoots while the buildup of sodium in plant tissue has the potential to interfere with enzymes participating in chlorophyll production, and the accumulation of both ions within plant tissue can reduce photosynthesis and growth [33–35]. The better growth performance of plants grown in cake-peat in our study may be due to the reduced pH and salt content of the cake-peat substrate. Organic contaminants in the process water were not measured; however, the higher organic carbon content of the peat is expected to also cause sorption of dissolved organics to the peat, reducing the toxicity of the water [36,37].

On the other hand, mixing cake with sand resulted in sodium, chloride, and carbonates concentrations comparable to levels found in cake. This is possibly due to the presence of soluble mineral material in the sand. Supply rates of nitrogen, phosphorus, and potassium were also generally low for cake-sand compared to the other substrates. Consequently, this caused poor growth of plants grown in the cake-sand substrate. Compensating

for nutrient deficiencies, e.g., through fertilization, should be combined with processes that reduce salinity, e.g., addition of organic matter to reduce evapotranspiration, in tailings reclamation.

Addition of process water to the tailings and tailings mixes adversely affected plant performance by reducing plant growth or increasing mortality. This may be due to the presence of naphthenic acids and salts in process water [35]. The combined impact of naphthenic acids and excess salts could exceed the sum of the individual effects of each of them [38] and increase water stress, interfere with respiration, and be toxic for organisms [35,39]. Leaf tip necrosis was observed in common herbaceous and woody forest plants grown hydroponically and subjected to undiluted process water treatment [40], possibly due to buildup of toxic compounds in the process water or nutritional deficiencies resulting from excess salts [40,41]. In our study, similar growth levels were observed between plants watered with reverse-osmosis water and those watered with equal proportions of centrate water and reverse-osmosis water. This suggests some interaction with process water will not be overly detrimental to the growth of plants.

We also found that the grasses had better growth performance than did forbs. Similar findings have been reported by Naeth and Wilkinson [42]. *H. vulgare* also had the best growth performance among all species. The ability of *H. vulgare* to germinate and establish on tailings under controlled conditions suggest that it is a good candidate for early tailings reclamation efforts, such as erosion control and phytoremediation [34]. *A. trachycaulum* showed good health across all treatments, but its aboveground biomass accumulation was less than *H. vulgare* over the study period. The slow growth of *A. trachycaulum* restricts the quantity of potentially toxic ions it can remove from contaminated soils [30]. It can, however, be used in combination with *H. vulgare* in reclamation efforts to increase vegetation cover, and consequently long-term stabilization [43] of tailings.

The native forb, *C. angustifolium*, has been suggested as a suitable species for reclaiming disturbed forests because it can establish on reclaimed soils (especially, a forest floor mineral mix) and capture soil nutrients effectively [44]. However, its growth on tailings and tailing mixes was the poorest, exhibiting the greatest mortality, and surviving plants showed average-to-poor health. This may be due in part to nutritional deficiencies of the tailings and tailing mixtures since seedling establishment of the species may be confined to areas that are rich in nutrients [45]. *C. angustifolium* growth was positively correlated with macronutrients (nitrates, phosphorus, magnesium), which supports the observation that the factors that influence successful establishment of *C. angustifolium* may be site and soil specific [44]. Reclaiming tailings with *C. angustifolium* will be a challenge because of its poor performance on tailings and potential soil specificity. *S. arvensis* exhibited better growth performance than *C. angustifolium*. However, its very slow growth on tailings makes it potentially less suitable for phytoremediation in these substrates compared to *H. vulgare* or *A. trachycaulum*. It should be noted that while *S. arvensis* may occur in reclaimed areas, it would not be specifically planted as it is classified as a noxious weed in Alberta [46].

Within each functional group, non-native species had better growth than native species. Naeth and Wilkinson [42] also found that non-native species had higher emergence and establishment on consolidated tailings than native species. Because native species are suited to the pre-disturbed ecosystem, their decline in novel environments following mining can be expected. However, native boreal species have been shown to exhibit varying tolerance to salt [47]. Salt tolerant population of *A. trachycaulum* can be found in a dry area, in Southern Alberta, with an underlying marine shale formation [48]. Understanding salt tolerance levels of native species as well as differences among accessions is important to determine their suitability for land reclamation [30].

## 5. Conclusions

This study tested the suitability of common boreal plants to the combined effect of fluid fine tailings cake, mixtures of tailings cake and reclamation substrates, and process water. Our results showed that mixing peat with cake tailings can reduce salinity and



improve plant growth. Additionally, *H. vulgare* and *A. trachycaulum* exhibited greater overall aboveground biomass and lower mortality and could therefore be suitable for initial reclamation of oil sands tailings. Because our study was performed under controlled greenhouse conditions, caution must be taken when extrapolating these studies to field sites where conditions such as extreme temperatures and competition exist.

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