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Circular economy side streams accelerate ecosystem recovery on mine tailings in northern conditions

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Abstract

Ecosystem restoration on mine tailings in northern conditions is constrained by limited availability of suitable cover materials, short growing seasons, cold winters and nutrient-poor substrates. Estimates indicate that natural till resources are insufficient to meet the cover structure needs of existing and closed mines, highlighting the need for alternative materials.

In summer 2024, a 1,200 m² restoration experiment was established on the Pahtavaara mine tailings area in Sodankylä, northern Finland. The study investigates whether circular economy side streams can replace part of the mineral cover material while accelerating vegetation establishment, improving water management, and supporting long-term ecosystem recovery in mine tailings.

Twelve 25 × 5 m strips were established in a randomised design. Growth media treatments included composted sewage sludge (CSS), CSS mixed with biochar, CSS mixed with sewage sludge ash (3 replicates each), and untreated control strips. Vegetation representing dry meadow, fresh meadow, flood meadow and willow shrub zones was introduced using container-grown seedlings and seed mixtures of local Nordic species. Additional strips with identical growth media were covered with locally sourced meadow cuttings. Stones and deadwood were added to create microtopography and microhabitats.

The first vegetation survey conducted in summer 2025 recorded plant survival, growth and flowering of planted individuals, as well as seedling emergence in permanent plots. Results showed unexpectedly high seedling survival, vigorous growth and successful germination across organic growth media treatments. After only one growing season, the site had developed into a local biodiversity hotspot, attracting a diverse range of pollinators and amphibians. Notably, larvae of the rare Lapland species Saturnia pavonia were observed.

The results demonstrate that circular bioeconomy side streams can significantly accelerate ecosystem recovery on mine tailings in northern environments while reducing reliance on natural till.

Keywords: *re-establishment, tailings, ecosystem restoration, circular bioeconomy, biochar, compost, northern conditions*

1 Introduction

Mine closure in the Nordic region increasingly faces a dual constraint: engineering covers must control water and oxygen fluxes through mine wastes, yet closure programs are expected to deliver stable, vegetated landforms that integrate into surrounding ecosystems (Lottermoser 2007). A key function of dry cover systems is to reduce infiltration and limit geochemical risks (e.g. acidification), while simultaneously providing a rooting environment that supports evapotranspiration and surface stability (Nicholls et al. 2019).

In Finland, cover designs have traditionally depended on glacial till as the main mineral component, often requiring substantial volumes per hectare because cover thickness is typically 0.3–1.8 m (European Commission 2018; Putkinen et al. 2017). When multiplied across tailings and waste rock footprints that can

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extend to tens or even hundreds of hectares, the resulting demand becomes very large at the scale of an individual mine for example, a 1.5 m cover thickness requires approximately 15,000 m^3 of till per hectare. This creates a practical challenge even in a country where till deposits appear abundant: the fraction of material that is accessible, suitable and environmentally acceptable for closure use can be much lower than the apparent resource. More broadly, the extensive reliance on natural soils and clays for cover construction has been identified as unsustainable and increasingly constrained at the global scale, driving the search for alternative materials. In addition, extraction of large volumes of till may itself cause environmental disturbance, further complicating the use of till as a primary cover material (Punkkinen et al. 2018).

A second bottleneck is biological. Forest-derived till is typically nutrient poor and low in organic matter and therefore may not promote rapid plant establishment (Heiskanen et al. 2020; Tordoff et al. 2000). Northern climates intensify this limitation through short growing seasons and prolonged snow cover, which restrict early growth and delay the development of a functioning vegetation layer (Niittynen 2020). Yet vegetation is not an optional ‘finish’: it is a process component of water balance control, supporting evaporation during the growing season, and potentially lowering percolation to underlying wastes.

Circular economy side streams offer a plausible route to address both constraints – reducing reliance on virgin mineral materials while improving the near-surface growth environment. Composted sewage sludge (CSS) provides organic matter and nutrients; ash can contribute alkalinity and nutrients; and biochar has been widely reported to improve plant performance particularly under stressful, low-fertility conditions while influencing soil biological activity (Hagner et al. 2021). From a restoration delivery perspective, the establishment method also matters: direct seeding is scalable but uncertain under harsh conditions, whereas planting nursery seedlings is typically more reliable but costlier; mixed strategies may therefore be needed in northern post-mining settings.

Here we report early outcomes from the Pahtavaara tailings restoration experiment in northern Finland, where compost-based growth media, with and without biochar or ash, were applied to the tailings surface and combined with locally adapted plant material and nature-based microhabitat elements. The purpose is to evaluate whether these circular economy–derived amendments can accelerate the first stages of vegetation establishment and ecosystem development under northern climatic constraints. The study includes 2 phases: large-scale revegetation and monitoring conducted during 2018–2024 (presented as background), and the 2024–2025 restoration experiment with vegetation surveys conducted in 2025.

2 Background: study site and prior revegetation trial

The Pahtavaara gold mine is located in Sodankylä municipality, approximately 35 km north of Sodankylä town centre, Finland (N 67.639098, E 26.439172). Mining operations were active between 1996 and 2014, after which the site has remained in a maintenance phase (Figure 1).

Figure 1 Old tailings site in Pahtavaara, Sodankylä

Notes: Map from National Land Survey of Finland (NLS), 2026. Location of the restoration experiment established in 2024 is marked with blue cross.

Based on a fertility analysis conducted in 2018 by Eurofins Agro using standard accredited laboratory methods. The tailings material is alkaline (pH 8.7) and highly calcareous, with a calcium concentration of approximately 17 mg l^{-1}. The analysed tailings sample contained no organic matter, and phosphorus concentrations were below the analytical detection limit (<1.5 mg l^{-1}). When interpreted using national soil fertility guidelines (Viljavuuspalvelu 2008), calcium content and pH both exceed levels considered high – even for clay soils. According to these guidelines, the phosphorus status is classified as poor, potassium as moderate, and magnesium as excessive. The magnesium-to-calcium ratio is favourable, whereas the magnesium-to-potassium ratio is excessively high. With respect to micronutrients, sulphur concentrations are high, boron availability is poor, copper status is moderate, manganese is satisfactory, and zinc availability is low.

Before establishing the 2024–2025 restoration experiment, the Pahtavaara tailings area had been used for pilot-scale and full-field revegetation testing. In 2018, a fertility assessment of the tailings was conducted, followed by small plot trials with different seed and fertiliser mixtures. Based on these results, large-scale revegetation of the tailings field proceeded in 2019 using light surface preparation and fertilisation without a separate growth layer. The implementation was carried out in 2 phases: an initial 10 ha test area used to compare surface preparation tools and work steps under varying moisture conditions, followed by a larger autumn sowing that covered approximately 50 ha. The latter involved surface harrowing, sowing of a clover–grass mixture and timothy, followed by delayed sowing of oats and synthetic fertiliser to avoid premature oats germination during warm weather, and final surface compaction using a roller. The applied seed–fertiliser mixture had a total application rate of approximately 550 kg ha^{-1}, consisting of ca. 390 kg ha^{-1} fertiliser (Y4) and ca. 160 kg ha^{-1} seeds (oats, timothy, and a clover–grass mixture). In autumn 2020, an additional 65 ha was seeded with timothy (25 kg ha^{-1}), and in 2021 fertiliser was applied to the area (183 kg ha^{-1}). The tailings area receives precipitation and snowmelt waters. Vegetation development was subsequently observed during 2020–2024, and plant material was sampled (2020, 2022, 2023 and 2024) for feed-quality and metal analyses by Eurofins Agro to assess its suitability for reindeer grazing.

During the first monitoring year (2020), vegetation cover on the tailings surface remained sparse and heterogeneous. Total plant cover in the permanent plots was typically low (≤15%), and species composition was dominated by sown grasses, scattered pioneer forbs, and early-colonising mosses. By 2021, a marked increase in surface cover was observed, driven largely by the rapid expansion of moss layers (*Ceratodon purpureus*) and dense grass growth in the better drained areas. In the most representative plots, total vegetation cover increased to approximately 95–99%, indicating effective surface stabilisation.

In the subsequent years (2022–2023), vegetation cover remained high and spatially continuous in these plots, but further changes in species composition were limited. The vegetation community remained structurally simple, characterised by a dominance of grasses and mosses, with relatively low vascular plant species richness. Although individual new species appeared sporadically over time, the overall assemblage showed little progression towards a more diverse meadow type or heterogeneous plant community. In contrast, poorly drained or intermittently flooded areas remained weakly vegetated throughout the monitoring period.

Overall, the baseline revegetation measures implemented between 2019 and 2023 successfully achieved rapid surface cover and physical stabilisation of the tailings. However, the resulting vegetation was largely uniform and functionally simplified, with limited development of structural complexity or habitat heterogeneity over several years. These outcomes provided an important reference condition for the subsequent 2024–2025 experiment, which explicitly aimed to accelerate ecosystem recovery beyond surface stabilisation by enhancing species diversity, microhabitat formation and early successional dynamics.

The analyses showed that concentrations of most trace metals in plant biomass remained low and below regulatory feed safety limits. Nickel and molybdenum concentrations were occasionally elevated in some years compared to reference sites, reflecting the geochemical background of the tailings. However, concentrations were below regulatory thresholds for feed safety. Levels of cadmium, lead, arsenic and mercury were generally low and close to analytical detection limits. Overall, the results indicated that revegetation did not lead to excessive metal accumulation in above-ground biomass during the monitoring period.

3 Materials and methods

3.1 Restoration experiment: experimental design and growth media characteristics

The new restoration experiment was established on the western edge of the tailings field in August 2024. The site is characterised by flat topography, nutrient-poor tailings material and exposure to wind, frost and seasonal water flow. A 1,200 m² experimental area was established around the discharge channel for run-off water, consisting of 12 parallel strips (25 m long × 5 m wide) arranged in a randomised design.

The following 4 treatments were applied:

1. control (no growth media)
2. composted sewage sludge (CSS)
3. CSS + biochar
4. CSS + sewage sludge ash.

Each treatment was replicated 3 times. In addition, a separate meadow cuttings (mulch) area was established using the same growth media treatments and covered with biodegradable erosion matting. The used growth medium consisted of composted sewage sludge produced at a municipal waste water treatment plant (Sodankylän Lämpö ja Vesi Oy). Biochar was produced from forest residues pyrolysis (GRK Finland Oy), and ash originated from sewage sludge (Neve Oy). Growth media mixtures were applied as an approximately 5 cm-thick surface layer. All materials complied with Finnish fertiliser product regulations.

3.1.1 Vegetation establishment and monitoring

Vegetation establishment was based on a zoned design reflecting local hydrological gradients and successional habitats typical of northern boreal meadows. Four vegetation zones were delineated within each experimental strip: willow shrub zone, flood meadow, fresh meadow and dry meadow. Species composition was selected among indicator species typical to different meadow zones to match the ecological requirements of each zone and to promote functional diversity (Table 1).

Table 1 Plant species used for revegetation in the Pahtavaara tailings experiment

Vegetation zone	Species (Latin name)	Seedlings per strip (25 × 5 m)
Willow shrub zone	*Salix phylicifolia*	*3*
	Salix lanata	*3*
	Alnus incana	*2*
	Betula pubescens	*3*
Flood meadow	*Filipendula ulmaria*	*7*
	Geranium sylvaticum	*14*
	Cirsium heterophyllum	*14*
Fresh meadow	*Silene dioica*	*14*
	Leucanthemum vulgare	*14*
	Vicia cracca	*14*
Dry meadow	*Linaria vulgaris*	*14*
	Campanula rotundifolia	*14*
	Solidago virgaurea	*14*
	Thymus serpyllum	*14*

Plant material consisted of a combination of container-grown seedlings and seed mixtures of locally adapted Nordic species provided by a local plant nursery. Each strip achieved similar number of seedlings and adjacent plots contained seeds of the same species (Table 1; Figure 2). Container-grown seedlings were used for key perennial species to improve establishment reliability under harsh site conditions, such as exposure to flowing water, while seed mixtures were applied to enhance spatial coverage and to promote natural regeneration. Seed mixtures and contained species characteristic of the respective meadow or shrub zones are listed in Table 1. Seeds of meadow species were applied at a rate of 2.0 kg ha^{-1}. In addition, seeds of *Festuca ovina* were applied (15 kg ha^{-1}) in the dry, fresh and flood meadow strips to support rapid vegetation coverage and reduce erosion. The strips with identical growth media treatments were also covered with locally sourced meadow cuttings collected from nearby semi-natural fresh meadow to introduce a broad propagule pool and associated microbial communities. Vegetation samples shown in Figure 3 represent mixed herbage collected at 2 time points (early and late summer) to ensure representation of species with different phenological timings (early- and late-flowering species). A preliminary investigation of meadow species was conducted before cutting; *Ranunculus acris, Taraxacum officinale, Achillea millefolium, Silene dioica, Filipendula ulmaria, Campanula patula, Anthriscus sylvestris, Geranium sylvaticum, Chamaenerion angustifolium, Alchemilla spp. Trifolium repens, Trifolium pratense, Rumex acetosa, Vicia cracca, Urtica dioica, Euphrasia spp., Plantago major, Solidago virgaurea, Trollius europaeus, Tanacetum vulgare, Thlaspi arvense, Alopecurus pratensis, Deschampsia flexuosa* and *Leontodon autumnal* were observed.

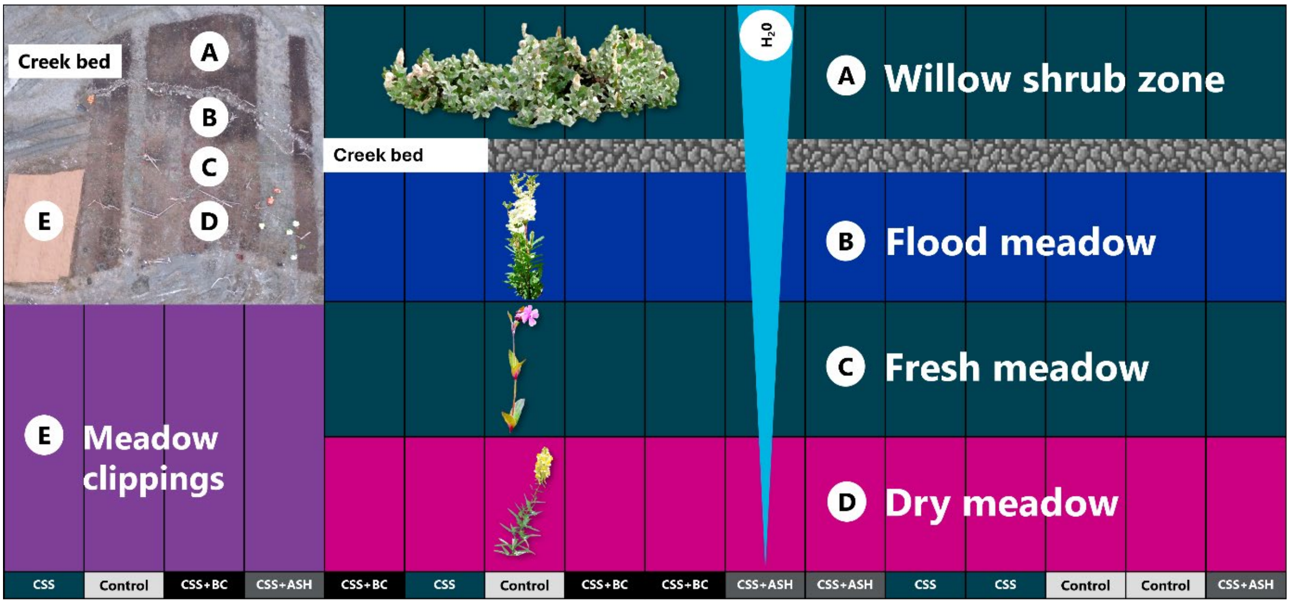

Figure 2 **Study design of restoration experiment consisting of various vegetation established from a combination of container-grown seedlings, seed mixtures and locally sourced meadow cuttings, following a zoned design reflecting hydrological gradients and successional habitats**

(a) (b)

Figure 3 **(a) Establishment of experimental site in August 2025; (b) Used meadow cut material harvested from nearby meadow in June and August to obtain seeds of early summer and late summer flowering species, evenly spread on the plot and covered with biodegradable fabric to stabilise the cut material**

To increase structural heterogeneity and create favourable microsites for plant establishment, stones and deadwood were placed on the surface to increase the naturally developed microtopography by flowing water. These elements were intended to generate small-scale variation in moisture, temperature and shelter, thereby supporting species with different ecological niches and improving overall establishment success.

Vegetation monitoring comprised survival and growth of container-grown seedlings, and quantification of regeneration of sowed seeds and meadow cuttings, including seeds. For container-grown seedlings, survival was recorded and plant height, width and number of flowering stalks were measured for 3 randomly selected individuals per species within each vegetation zone. For regeneration of sowed seeds and seeds from meadow cuttings, permanent 25 × 25 cm plots were established in seeded and meadow cutting areas, where all emerged seedlings were counted. All vegetation surveys were conducted during the peak growing season in summer 2025 (and will be done in 2026). These surveys relate to the 2024–2025 restoration experiment. Plant cover was not quantitatively assessed, as the focus of the first-year monitoring was on seedling survival, growth and regeneration rather than full community composition metrics. Pollinators were opportunistically observed but not systematically surveyed.

4 Results

4.1 Ecosystem restoration experiment

Vegetation establishment was high after the first growing season in 2025. Seedling survival and growth were high across all organic growth media treatments, while control strips showed markedly weaker development. Differences between compost-only and compost-based mixed media were less pronounced than contrasts between amended and unamended substrates (Figure 4) (when including all species: $p<0.05$ between control and all organic amendments). For example, in the willow shrub zone, the average width of *Betula* was 10–12 cm and the average width of *Salix* was 12–16 cm in organic amendments, compared to 8–9 cm and 6.8 cm in the controls, respectively.

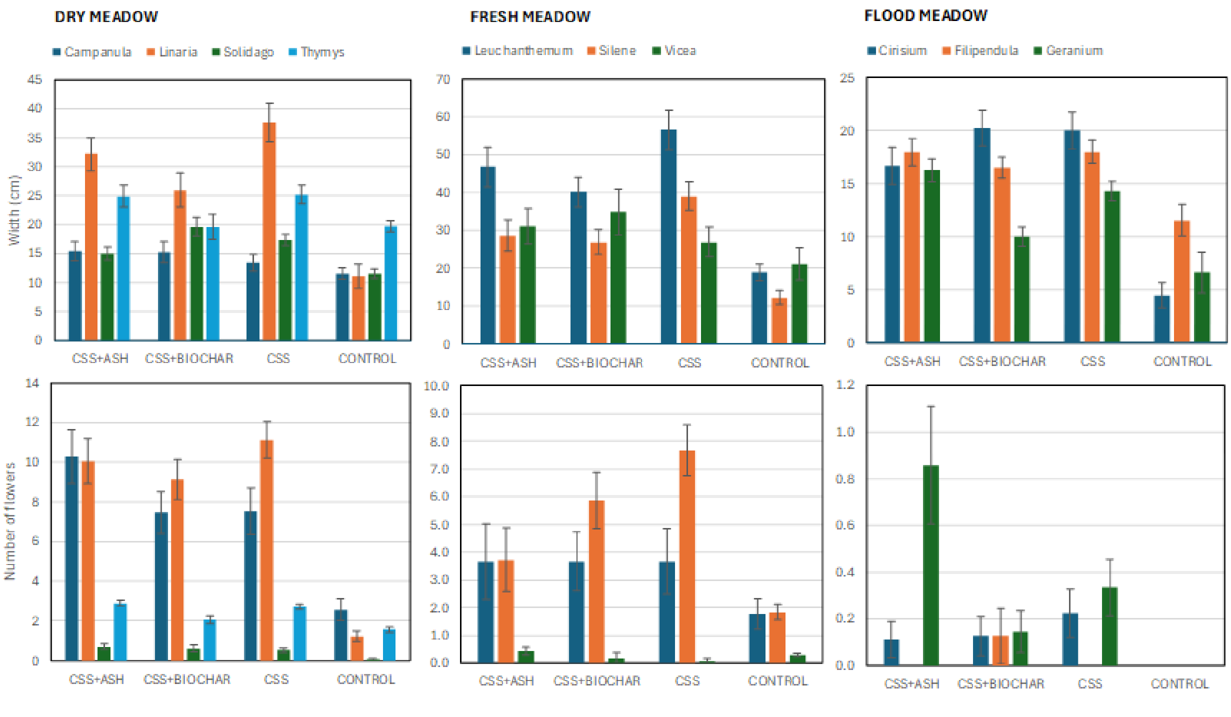

Figure 4 Mean (±standard error) width (cm) and number of flowers (in case of *Thymus* flower stems) of the seedlings of dry (a), fresh (b) and flood (c) meadow species after one growing period in 2025. Seedlings were planted in various growth media treatments including sewage sludge compost (SCC), biochar and ash or left without growth media (Control) in Pahtavaara tailings site (n = 18)

Seed emergence during the first growing season differed clearly between growth media treatments. Plots amended with compost-based growth media showed higher seedling emergence than the untreated control, where germination of both selected meadow species and grasses remained sparse (Figure 5). When counting the total number of emerged seeds, the difference between control and each organic growth media was statistically significant both for meadow and grass species ($p<0.05$). However, no significant difference existed between organic growth media ($p>0.05$). Seedling emergence was particularly strong in fresh meadow zones and in plots treated with compost-based growth media. Thus, in general biocover solutions improved both plant germination and growth. However, the emergence of *Leuchantehmum* seeds was higher in controls than in the applied growth medium (Figure 5).

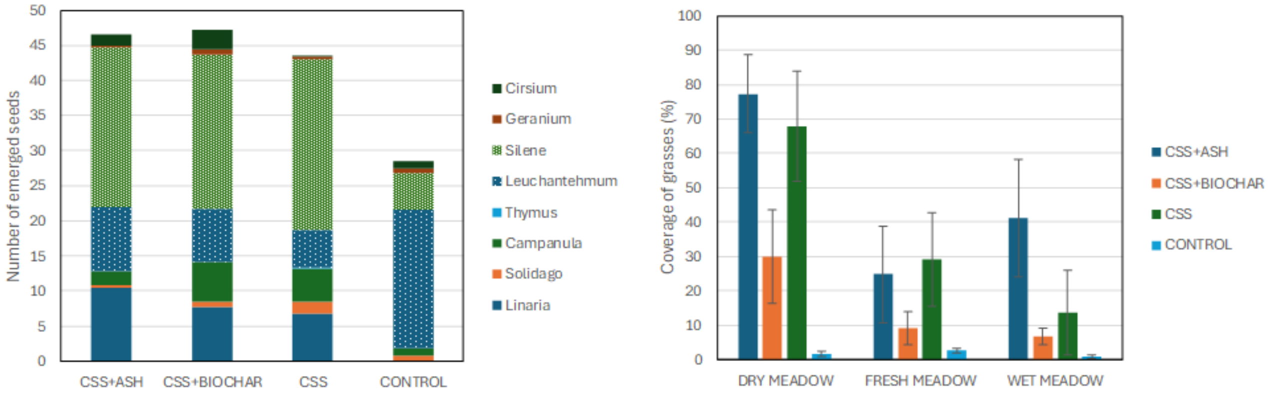

Figure 5 Mean (±standard error) number of seedlings (dry, fresh and flood meadow species) emerged from seeds sown in various growth media treatments (in 25 × 25 cm plots) including sewage sludge compost (SCC), biochar and ash or left without growth media (Control) in Pahtavaara tailings site (n = 18) after one growing period in 2025

In the first growing period, the meadow cutting treatments showed rapid colonisation by a diverse assemblage of herbaceous species with total coverage of ~30%, including seedlings of 12 species. In comparison, the advanced tailings site had only 6 species. The most abundant species were *Ranunculus acris, Rumex acetosa, Phleum pratense* and *Leontodon autumnalis.*

The site demonstrated promising early biodiversity responses within 12 months, with abundant flowering that attracts a diverse range of pollinators. Amphibians were observed in moist zones, and larvae of the rare Lapland moth *(Saturnia pavonia)* were recorded (Figures 6 and 7).

(a) (b)

Figure 6 (a) Experimental site before ecosystem restoration;(b) Experimental site 12 months later

Large-scale revegetation implemented in 2019 rapidly increased surface cover on the tailings, driven mainly by dense growth of *Phleum pratense* and extensive moss layers (*Ceratodon purpureus*), with limited increase in vascular plant species richness and little progression towards a heterogeneous meadow-type community. Poorly drained areas remained weakly vegetated, highlighting effective surface stabilisation but limited ecological complexity prior to the 2024–2025 experiment.

Figure 7 Promising early biodiversity responses within 12 months, with abundant flowering that attracts a diverse range of pollinators

5 Discussion

The Pahtavaara field experiment demonstrates that the addition of organic, circular economy–derived growth media can substantially enhance early vegetation establishment on mine tailings under northern climatic conditions. This observation is consistent with previous studies showing that nutrient-poor mineral substrates, including tailings and glacigenic till, often represent a major bottleneck for plant establishment unless amended with organic matter and nutrients (Tordoff et al. 2000; Heiskanen et al. 2020).

Composted sewage sludge is a plausible driver of the rapid early response observed at Pahtavaara, as it increases organic matter content, nutrient availability and water-holding capacity in the near-surface layer – factors repeatedly identified as critical for revegetation success on mine wastes and tailings covers (Lottermoser 2007; Heiskanen et al. 2020). In field conditions similar to northern Finland, compost amendments have previously been shown to markedly enhance plant survival and biomass production compared with unamended till or tailings substrates (Hagner et al. 2021).

The co-amendments tested at Pahtavaara – biochar and sewage sludge ash – are also supported by earlier research as functional modifiers of growth media. Biochar additions have been widely reported to improve plant performance under stressful, low-fertility conditions, particularly when combined with organic amendments, while also influencing nutrient retention and metal bioavailability (Biederman & Harpole 2013; Hagner et al. 2021). Ash, in turn, can contribute alkalinity and nutrients, thereby modifying pH and nutrient dynamics in surface layers, which may be especially relevant on chemically extreme tailings substrates (Lottermoser 2007). Although treatment differences between compost-only and compost-based mixtures were modest after one growing season, the overall response supports the concept of tailoring growth media functions rather than relying solely on mineral cover materials. However, species selection is also critical and should be tailored to site conditions, as not all species benefit from organic amendments. For example, the emergence of *Leucanthemum* seeds was higher in control than in the organic matter–amended growth medium, indicating species-specific responses.

The promising early biodiversity responses may be partly explained by the application of dynamic plant design/vegetation planning. This approach involves designing planting zones to moisture gradients and adaptable plant communities that are expected to grow, shift and self-regulate over time in response to natural processes such as changes in climate, soil conditions and water availability. Such a planning approach is characteristic of ecological restoration practices (Dunnet & Hitchmough 2004).

From a mine closure perspective, rapid vegetation establishment has implications beyond surface aesthetics. Vegetation plays an active role in the water balance of mine covers through evapotranspiration and rainfall interception, potentially reducing percolation into underlying waste materials (Nicholls et al. 2019). Studies on waste rock piles have demonstrated that vegetated surfaces exhibit substantially higher evapotranspiration rates than bare substrates, supporting the inclusion of vegetation as a functional component of closure systems rather than a purely cosmetic end point (Nicholls et al. 2019). It should be noted that the rapid vegetation response observed during the first growing season may partly reflect the high nutrient availability in the applied organic growth media. In many restoration systems, such initial responses can be followed by a decline in biomass or vigour if internal nutrient cycling processes are not yet established. However, in the present study, the use of organic amendments, meadow cuttings and structural elements was intended to promote not only initial plant establishment but also longer-term development of biological processes. A potential limitation of the applied approach is that shallow organic surface layers may degrade over time due to decomposition, potentially leading to reduced nutrient availability and structural stability. In many restoration systems, this can result in declining vegetation performance if internal soil processes are not established. In the present study, however, the use of compost-based growth media was combined with meadow cuttings, diverse plant species and structural elements (e.g. stones and deadwood) to promote the development of biological and physical heterogeneity. These features are expected to support the gradual establishment of nutrient cycling processes and more self-sustaining vegetation over time. Continued monitoring will be required to evaluate whether these systems develop towards self-sustaining vegetation communities and whether the system develops towards stable ecosystem functioning under northern conditions.

The Pahtavaara results also highlight the importance of structural and biological heterogeneity in early restoration. The deliberate inclusion of stones and deadwood to create microtopography and microhabitats aligns with broader restoration literature emphasising that small-scale heterogeneity can promote diverse establishment niches across moisture and temperature gradients, thereby supporting higher species richness and functional diversity over time (Lottermoser 2007; Tordoff et al. 2000). While such measures are rarely isolated experimentally, they are consistent with ecosystem-scale closure goals that aim for self-sustaining, heterogeneous communities rather than uniform vegetation cover.

Restoration method choices remain a key consideration for scaling revegetation in northern mine environments. The literature consistently shows that direct seeding is cost efficient and scalable but often associated with lower and more variable establishment success, whereas planting container-grown seedlings typically results in higher survival but at greater cost (Palma & Laurance 2015; Butterfield & Munson 2023). The mixed strategy applied at Pahtavaara – combining seedlings, seed mixtures and meadow cuttings – reflects recommendations from synthesis studies suggesting that hybrid approaches can balance reliability, diversity and cost efficiency, particularly under harsh environmental conditions (Palma & Laurance 2015; Leverkus et al. 2021). By combining early and late season sampling for meadow cuts, the dataset captures vegetation across phenological stages, reducing bias related to seasonal variation in plant composition and element concentrations.

Finally, the rapid emergence of flowering vegetation and associated fauna observed at Pahtavaara within one growing season suggests that functional growth media, diversified establishment methods and dynamic plant design can compress the time required to reach key ecological milestones in mine closure. Previous studies on compost- and biochar-amended tailings have similarly reported accelerated progression from sparse vegetation cover towards more biologically active systems, without evidence of problematic metal accumulation in plant biomass during early stages (Hagner et al. 2021). Although pre-vegetation trials conducted in the site showed that some trace element concentrations (particularly nickel and molybdenum) were elevated in some plant samples relative to reference sites, values remained below regulatory thresholds. These results, taken together, indicate that trace element concentrations remained within safe limits during the monitoring period and therefore do not suggest a significant metal-related risk at this stage of ecosystem restoration. Nevertheless, longer-term monitoring is required to assess whether early treatment effects persist, whether trace element uptake is stable, how successional trajectories evolve through multiple winters, and how vegetation development feeds back to hydrological performance and long-term closure stability, as well as cost efficiency of the diversified establishment.

6 Conclusion

The results demonstrate that circular economy side streams can significantly accelerate early vegetation establishment on mine tailings under northern climatic conditions. The use of compost-based organic growth media reduced dependence on natural till while simultaneously improving plant establishment, growth and early ecosystem development. Biodiversity responses were rapid, with the restored site functioning as habitat for pollinators and amphibians within a single growing season. The combination of functional growth media, microtopography and dynamic vegetation planning shows strong potential for supporting ecologically robust and sustainable mine closure solutions in northern regions.

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