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Selecting effective plant species for the phytoremediation of persistent organic pollutants and multielement contaminated fibrous sediments

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Abstract

Background Wastewater discharges from the old pulp and paper industry led to the accumulation of contaminated wood pulping fibers and debris—referred to as fiberbanks (FB)—in the Baltic Sea and freshwater bodies across Sweden and other pulp-producing countries. These anthropogenic sediments are polluted with toxic metal(oid)s and persistent organic pollutants, and their decomposition releases greenhouse gases. Phytoremediation offers a nature-based solution for the ex-situ treatment of these fibrous sediments, but they present unique challenges due to the abundant and unstable organic matter and aged pollution. This study aims to identify potential plant candidates and to address the limitations of fiberbanks as a plants growing media for phytoremediation.

In a greenhouse experiment, we assessed the performance of five plant species (*Brassica juncea*, *Brassica napus*, *Helianthus annuus*, *Hordeum vulgare*, and *Poa annua*) grown in substrates formulated with fiberbank. The evaluation included plant growth parameters, bioconcentration and uptake efficiency of metal(oid)s (V, Cr, Co, Ni, Cu, Zn, As, Cd, and Pb), and the degradation of polycyclic and linear hydrocarbons.

Results Despite initial concerns, fiberbanks displayed favorable physical characteristics and a degree of fertility conducive to plant growth. Even though all tested species seeds could cope with fiberbanks acute toxicity, *H. vulgare* and *P. annua* showed better tolerance to the fiberbanks substrates and superior aerial biomass development, which promoted a highest toxic metal(oid)s uptake efficiency, regardless of lower bioconcentration factors for most of the target elements. Zn (17.16–23.25 mg/kg of FB), Cu (4.18–6.48 mg/kg of FB) and Cr (1.05–1.36 mg/kg of FB) were most effectively taken up by these plants. The uptake of Co (0.04–0.18 mg/kg of FB) and Ni (0.05–0.17 mg/kg of FB) was lower. As (0.01–0.02 mg/kg of FB), Cd (0.02–0.06 mg/kg of FB), Pb (0.02–0.04 mg/kg of FB) and V (0.02–0.03 mg/kg of FB) phytoextraction was not significant. None of the species exhibited a significant removal of targeted organic pollutants.

Conclusions Phytoremediation, either on its own or in combination with other strategies, shows promise for the remediation of fiberbanks. However, further research is needed to understand how the organic matrix and long-term underwater aging of fiberbanks affect pollutants bioavailability.

Keywords Fiberbanks, Multielement pollution, Organic pollutants, *Brassica juncea*, *Brassica napus*, *Helianthus annuus*, *Hordeum vulgare*, *Poa annua*

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Background

Until more stringent regulations emerged in 1969, unregulated wastewater discharges from the old Swedish pulp and paper industry led to the creation of deposits of polluted fibrous sediments on the Baltic Sea floor and in lakes and rivers across central and northern parts of Sweden. Fibrous sediments include fiberbanks (as usually referenced in the Scandinavian literature), which are deposits that can have several meters of accumulated lignocellulosic fibers and wood chips or sawdust residues, and the fiber-rich sediments located around them [4, 42]. These anthropogenic, organic-rich sediments are typically mixed contaminated with metal(oid)s of high environmental concern and with persistent organic pollutants (POPs), like polychlorinated biphenyls (PCBs), chlorinated pesticides (such as DDTs and HCB) and polycyclic aromatic hydrocarbons (PAHs), originated from the wood pulping processes and other associated factories situated nearby the pulping mills.

Approximately 10.8 million tons of contaminated fiber material were discharged into Sweden's aquatic environment over the past century, resulting in fiberbanks covering an estimated area of 2.5 million m² and for fiber-rich sediments about 26.5 million m² across seabeds, rivers, and lakes in Sweden's northern counties [4, 42]. Similar issues are reported in Finland, Norway, Canada, and the USA, highlighting that polluted fibrous sediments are a widespread, yet insufficiently addressed environmental concern [15, 37, 29, 33]. Located mostly in shallow waters, these sediments are vulnerable to resuspension through natural or anthropogenic process, which can increase pollutant dispersion and pose ecological and human health risks, especially near urban or recreational zones [18, 29]. Furthermore, the anoxic conditions within fiberbanks promote methylmercury formation [50]) and the emission of greenhouse gases like methane and carbon dioxide, with an estimated release from Swedish fiberbanks potentially accounting for up to 7% of the country's total known GHG emissions in 2021 [38].

Metal(oid)s (such as Pb, Cd, Cr, Cu, Ni, Zn, Co, Ba, Hg or As), were released in the wastewater together with by-products from the pulping processes, such as pyrite ashes from the nowadays outdated sulfite-cooking process. Mercury, for instance, was used as a biocide and a catalyst in the pulp bleaching. PCBs were used in materials associated with the carbonless copy paper production. DDTs and HCBs were widely employed as insecticides and fungicides in the forest industry until banned in Sweden in the 1970s. The PAHs presence in fiberbanks can be attributed to fuel leakages from the factory facilities, but also to other varied sources since they are formed out of incomplete combustion of organic materials. Other high concern pollutants such

as polychlorinated dioxins and furans originated from wood preservatives, can also be tracked down in fiberbanks samples [5, 17, 18, 25].

Management alternatives for these sediments are currently under discussion, and include monitored natural attenuation, in situ capping [19] or careful dredging and ex situ treatment [32]. In this last scenario, before the contaminated material is deposited on shore, proper ex situ treatment alternatives must have been assessed, since these sediments present unique characteristics linked to their high organic matter content and mixed variable pollution pattern. Phytoremediation strategies are nature-based solutions that tend to be more sustainable than physical and chemical techniques since they can often be carried out with less resource input and therefore be more cost-effective. Besides, they have better public acceptance and a smaller environmental footprint [34]. Phytoremediation can be particularly effective for simultaneously degrading and removing organic and inorganic pollutants from a co-contaminated solid matrix, by means of phytoextraction and phytodegradation mechanisms within the plant tissue, or in the rhizosphere with the help of associated microbial communities (rhizodegradation) [13, 31]. In addition, very little energy input is required, and plants can aid in sequestering carbon and be reused as a renewable energy source after harvesting [41]. This makes the potential use of the technology more appealing and feasible especially for the Swedish fibrous sediments case, where the liability for environmental harm is not clear yet [32, 60].

The use of plants has been well studied as a biological technique for the remediation of contaminated soils and sediments [28].

However, there are currently no references available on the application of phytoremediation technologies to this specific type of fibrous sediment, with such a high content of organic matter. Moreover, this organic matter is still undergoing degradation, and the associated pollutants have experienced aging processes for nearly fifty years under water. Currently, there is very limited—or even no—information on how these conditions influence the bioavailability or chemical state of the target pollutants for any bioremediation purposes. On the other hand, physical and chemical properties of material batches for cleaning up could vary greatly, depending on whether it consists primarily of polluted lignocellulosic fibers or a mixture of fibers and mineralogenic sediments. In addition, the synergistic or antagonistic effects of mixed toxic metals and organic contaminants on plant growth and remediation efficiency can be variable [11], amplifying the challenge to create adequate conditions for plant growth and phytoremediation success in fibrous sediments.

The primary objectives of this study were: (i) to address the limitations of fiberbanks to be used as a plant growing media; (ii) to identify potential plant candidates suitable for fibrous sediments ex-situ phytoremediation; (iii) to assess the ability of selected plants to uptake target toxic metal(oid)s and degrade organic pollutants present in fiberbanks.

Methods

Fiberbanks sampling and pretreatment

Fiberbank material was collected from Sundsvalls Bay in the Gulf of Bothnia, Sweden. This area was historically affected by industrial activities, primarily from the Ortviken sulfite pulp mill factory, a nearby sawmill, and related activities. A 500 L bulk sample was collected using a two-meter-long core tube sampler at a water depth of 18 m. The sample was taken from the easternmost fiberbank in the bay (Fig. 1), which spans an area of 45,000 square meters and contains a 6 m-thick layer of waste cellulose fibers [4]. The collected fiberbank material dewatering was conducted for 5 days in a 1 m³-container equipped with gravel and a geotextile bed.

After dewatering, the material was air-dried under a fume hood at approximately 20 °C for 7 days, then ground and sieved through an 11 mm mesh. Representative samples of the fresh dewatered material, the air-dried fiberbank, and the runoff water were sent to an external laboratory (Eurofins Environment Testing Sweden AB) for a comprehensive environmental hazards screening

covering 161 parameters. This screening included analysis for various pollutants such as aliphatic and polycyclic aromatic hydrocarbons, volatile organic compounds (VOCs), phenols, organochlorine pesticides, PCBs, selected herbicides, methylmercury, and toxic metals and metalloids. During the dewatering process, there was minimal washing out of pollutants, with only around 10% of the original concentration of Benzene detected in the runoff water sample. The air-drying process did not significantly alter the concentrations of most contaminants, except for methylmercury, which decreased by approximately 50% in the dried material (Table SM1, Supplementary Material).

Selected plants species and fiberbanks phytotoxicity

Five plant species were selected for the phytoremediation tests in fiberbanks based on the specific criteria: (i) the ability to accumulate multiple metals, (ii) extensive root systems for organic pollutants degradation, (iii) suitability for growth in Nordic climatic conditions, and (iv) potential for post-harvest biomass reuse. The chosen species were *Brassica juncea* L. (Indian or salad mustard) and *Brassica napus* L. (canola) from the Brassicaceae family; *Hordeum vulgare* (barley) and *Poa annua* (tall meadow or blue grass) from the Poaceae family; and *Helianthus annuus* L. (common sunflower) from the Asteraceae family.

Brassica species are known for accumulating Zn, Cu, Ni, Cd, and Pb [9, 35, 47]. Particularly, *B. juncea* varieties,

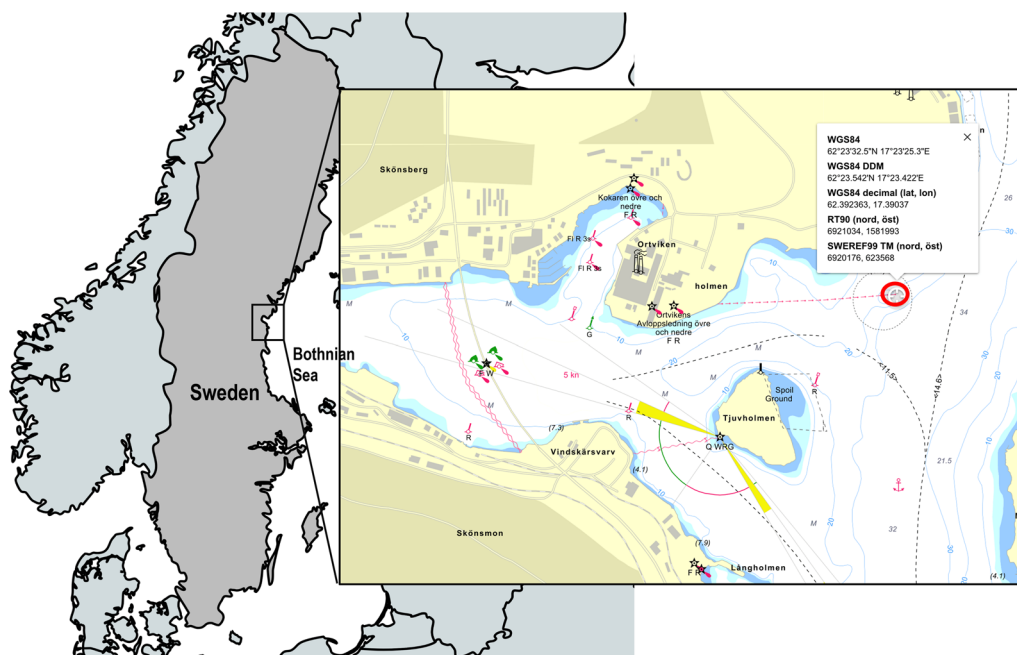


Fig. 1 The Fiberbank sampled in Sundsvall's Bay in the Bothnian Sea (WGS84: 62°23'32.5" N, 17°23'25.3" E), is indicated with the red circle

have shown promise in Hg uptake [45, 49]. Postharvest uses for *B. juncea* include spice crop seeds and fodder, while *B. napus* oil serves as high-quality vegetable edible oil for various purposes. Poaceae grasses, are potential candidates for phytoextraction due to their extensive root systems, high biomass yields, fast growth rates and adaptations to harsh environments [44]. Particularly, *Poa annua* has demonstrated bioaccumulation abilities for Pb, Zn, Cd, As, and Hg [6, 16]. Barley (*Hordeum vulgare*) has demonstrated the ability to uptake arsenic, which is usually a problematic target for phytoremediation trials [39]. Barley grains have several uses in food production, particularly in beer breweries. *Helianthus annuus*, showed to be able to cope with and uptake several toxic metals, exhibiting good bioconcentration factors (i.e. bioconcentration values close to or higher than 1) for Zn, Pb, and Cd [12, 14]. The sunflower offer various postharvest uses, such as biomass for energy production or seeds for common edible oil extraction.

Seeds from selected plant species were obtained from local organic suppliers, checked for anomalies, and sieved for uniformity with no further pretreatment. Seeds viability testing showed over 70% germination potential in distilled water for all the plant species. A commonly used phytotoxicity test based on the Zucconi method [20, 62], was employed. After stabilization in the dark for 24 h, a suspension of 1:10 fiberbank/water ratio (referred to as “100% water-extract”) was filtered and diluted to 60, 30, and 10% with distilled water. Ten to twenty seeds of each selected plant species were incubated (7 days at 25 ± 2 °C) by quadruplicate in Petri dishes with 3 ml of each of the dilutions or with water for germination control. Germinated seeds (radicle length > 5 mm) were counted, and root elongation was measured. The Germination Index was calculated using the following Eq. (1):

$$GI(\%) = \left(\frac{Ge Le}{Gc Lc} \right) * 100 \quad (1)$$

where Ge is the number of germinated seeds in the fiberbank extracts; Gc is the number of germinated seeds in distilled water; Le is the average value of root length in fiberbanks extracts in mm; and Lc is the average value of root length in the control plates (mm).

Experimental design

A phytoremediation trial was conducted in a controlled greenhouse setting using a two-factor factorial design (i.e. substrate type and plant species). Different types of plant substrates were formulated for the phytoremediation trials using fiberbank (FB) material (air-dried, ground, and sieved to < 11 mm) and sand (sieved to < 2 mm), while control treatments were prepared using sand and unamended Sphagnum

peat with a fine-to-medium grain size. These substrate components were mixed in different proportions and adjusted to achieve the physical properties recommended as suitable for soilless plant culture: total porosity (TP) ≥ 70 –85%; 55–70% water retention capacity (WRC); 10–30% air porosity (AP), and bulk density < 0.5–0.6 [7, 61]. These physical properties were assessed using a porometer following the methods proposed by Fonteno and Bilderback [24] and Wallach [61].

Following preliminary phytotoxicity assessments, which showed low toxicity of the fiberbank material for all the chosen plant species, and considering the optimal values for the physical properties previously mentioned, four substrate mixtures were selected for the trial. Two of these contained fiberbank material at 70 and 90% by volume (with the aim of maximizing the proportion of fiberbank material used to improve treatment efficiency) and 30 and 10% of sand, respectively. The other two mixtures served as controls treatments in which fiberbank was replaced with an equal volume proportion of peat (70 and 90%). Details of weight and volume formulations for the selected four substrates are provided in Table 1.

Representative samples of the selected substrates were analyzed for chemical characterization. The organic matter (OM) content was analyzed by the loss on ignition (550 °C) method. Electrical conductivity (EC) and pH were measured potentiometrically in 1:10 water-extraction ratios. Nutrients content analyses included total nitrogen (TN; N-Kjeldahl + deardas method), ammonium nitrogen (N-NH₄; APHA Method 4500, 1998), and total P, Ca, K, Mg and S which were extracted in aqua-regia and determined by ICP-AES (method ISO 11466/EN13346 mod. ICP-AES). The concentration of target toxic metal(oid)s in the formulated substrates and in the base fiberbank material were analyzed according to the procedure described in Sect. “Samples digestion and analysis of target metal(oid)s content”. The results of the substrates’

Table 1 Plant substrates formulation for phytoremediation trials

Substrate	Volume (cm ³)		Weight (g dm)		Total weight (g/L)
	FB/peat	Sand	FB/peat	Sand	
70% FB	700	300	57.0	470.0	527.0
70% peat	700	300	60.1	470.0	530.1
90% FB	900	100	68.2	147.1	215.3
90% peat	900	100	77.2	147.1	224.3

Volumetric and weight proportions per liter of substrate
dm: dry mass

physical and chemical characterization are presented in Table 2.

Individual plastic pots, each equipped with a tray for recirculating lixivate, were filled with 700 mL of each of the four substrate types, with five replicates for each of the five plant species, totaling 100 pots. Before sowing, pots were bottom watered overnight until the container reached water capacity saturation. Five seeds of *H. annuus*, 20 seeds of *B. juncea* and *B. napus*, 16 seeds of *H. vulgare* and 0.5 g of *Poa annua* seeds were sown in the corresponding pots. Pots were watered to maintain 60% container capacity throughout the experiment, with controlled ambient temperature (25 ± 5 °C) and humidity (35–50%) in the greenhouse and supplemented by artificial lighting for 12 h/day. After seedlings emergence (9–12 days, depending on the species), 3 g of a granulated slow-release fertilizer (NPK 14–4, 4–10, VitaGro, Protect Garden™) were added to each pot.

Thinning was applied to both Brassicas species and the sunflower to achieve desired plant densities in the pots

(4 and 3 plants per pot, respectively). In addition, all pots were randomly rotated on the greenhouse tables each week to ensure uniform exposure to environmental conditions. All plants were harvested 75 days after sowing. The aboveground tissues were washed with distilled and ultra-pure (type-1) water, dried at 80 °C for 48 h and weighed. Despite multiple attempts using various reagents and methods, the roots could not be adequately separated from the substrate due to heavy entanglement with the fiberbank material. As a result, root biomass and its metals content could not be measured, though one composite substrate sample per pot was freeze-dried for the analysis of residual organic pollutants following the methods described in Sect. “Organic pollutants analyses”.

Samples digestion and analysis of target metal(oid)s content

Aerial biomass and fiberbank substrates triplicate samples were ground to a homogeneous powder and acid digested in closed vessels in a microwave system (Milestone-ETHOS EASY Systems, SK-15 high-pressure rotor)

Table 2 Physical and chemical characterization of substrates formulated with fiberbank

	70% FB	70% peat	90% FB	90% peat	FB
AP (%)	8.2 (1.1)	3.2 (0.9)	17.6 (0.5)	6.9 (0.7)	19.5 (2.9)
WRC (%)	55.9 (0.4)	67.6 (1.1)	58.5 (0.8)	70.7 (1.2)	62.5 (3.2)
TP (%)	64.1 (1.2)	65.2 (1.5)	76.1 (1.0)	77.6 (1.5)	82.0 (0.4)
BD (g/cm ³)	0.6	0.5	0.3	0.2	0.1
OM (%)	4.3	10.7	28.9	30.5	92.5
pHw	5.6 (0.04)	4.7 (0.06)	5.4 (0.02)	4.5 (0.05)	5.4 (0.03)
EC (mS/cm)	2.4 (0.3)		6.2 (1.3)		6.4 (0.2)
TN (g/kg)	0.96	0.92	1.7	2.1	6.5
N-NH ₄ (g/kg)	< 0.1	< 0.1	0.17	0.23	0.6
P (g/kg)	0.23	0.22	0.31	0.33	0.49
Ca (g/kg)	3.8	4.2	3.8	4.9	2.3
K (g/kg)	1.4	1.3	1.2	0.86	1
Mg (g/kg)	3	2.7	2.9	2.3	2.6
S (g/kg)	0.8	0.29	4.5	0.66	9.8
As (mg kg ⁻¹)	0.98 (0.11)		1.11 (0.04)		1.01 (0.01)
Cd (mg kg ⁻¹)	0.16 (0.03)		0.21 (0.01)		0.37 (0.01)
Co (mg kg ⁻¹)	3.95 (0.48)		3.33 (0.21)		0.70 (0.10)
Cu (mg kg ⁻¹)	3.65 (0.14)		11.73 (0.30)		20.56 (0.53)
Cr (mg kg ⁻¹)	83.48 (16.04)		119.03 (2.9)		29.41 (0.2)
Hg (mg kg ⁻¹)	< 0.040		< 0.040		0.055 (0.005)
Ni (mg kg ⁻¹)	12.92 (2.25)		13.75 (1.44)		9.47 (0.59)
Pb (mg kg ⁻¹)	9.74 (1.42)		8.40 (0.30)		5.35 (0.17)
V (mg kg ⁻¹)	27.66 (3.15)		21.31 (1.57)		5.47 (0.28)
Zn (mg kg ⁻¹)	17.67 (2.61)		29.83 (1.57)		57.64 (1.80)

Values are the mean of triplicates and expressed on a dry weight basis; SD is indicated in parenthesis. Variation coefficients for OM% and nutrients content results are 10–20%

FB: Air-dried, ground sieved < 11 mm fiberbank; AP: Air Porosity; WRC: Water Retention Capacity; TP: Total Porosity; BD: Bulk density (calculated on a dry weight basis)

with a mixture of HNO_3 (65%)/ HCl (30%) (3:1) and HNO_3 (65%)/ HF (50%)/ HCl (30%) (3:1:1), respectively. Each digestion batch included a digestion blank and a certified reference material for plant samples (Rye Grass-ERM-CD281) and for fiberbanks or substrates samples (Sewage Sludge-BCR-145R). The digestion was completed with two steps of 15 min, at 200 °C and 1800 watts.

After digestion, an aliquot of the cooled down digest was diluted with ultrapure (type 1) water. The content of V, Cr, Co, Ni, Cu, Zn, As, Cd, Hg and Pb in the prepared solutions was determined by inductively coupled plasma-mass spectrometry (ICP-MS) on an Agilent 7700×series model (Agilent Technologies Sweden AB) equipped with an Octopole Reaction System (ORS3). For mercury determination, a preservative gold solution (2 ug/ml) was added when diluting samples, blanks, reference materials, and calibration standards.

The USEPA-SW 846-standard methods (USEPA 1996, 2007c, 2014) guidelines were followed for samples digestion and analyses. All acid reagents were of trace metal analytical grade (Supelco® Merck) and used without further purification. Type 1-ultrapure water was used for all the dilutions. All glassware was cleaned by soaking overnight in 5% HNO_3 , rinsed twice with distilled water and once with ultrapure water and oven-dried before use. Multielement standard solutions were purchased from Sigma-Aldrich and the gold preservative solution for mercury from VHGM™.

Organic pollutants analyses

Organic pollutants were extracted from 2 g of freeze-dried samples of the substrates before and after plant growth, using accelerated solvent extraction (ASE 350—Dionex Corp., Sunnyvale, USA). Two extraction cycles were performed with dichloromethane/hexane and hexane/acetone solvents systems. Extracts were purified in a silica gel cartridge (Strata® SI-1 Silica, 55 µm, 70 Å) by eluting with dichloromethane/hexane, then concentrated and solvent-exchanged to hexane. Pretreatment with activated copper beads was used for sulfur removal in the extracts. Clean extracts were analyzed using gas chromatography coupled to a single quadrupole mass spectrometer (GC–MS/Agilent Technologies-GC 6890N) in Selective Ion Monitoring (SIM) mode and with a Varian VF5ms capillary column of 30 m×0.25 mm (inner diameter) and 0.25 µm (thickness). Pulsed splitless injection mode was used together with an inlet temperature kept at 300 °C. Oven temperature program was: 50 °C, hold 0.5 min, ramped up by 25 °C/min to 290 °C and a second ramp at 5 °C/min to 320 °C (held for 5 min).

Twenty chlorinated pesticides, seven PCBs, 16 PAHs, and 10 aliphatic hydrocarbons were targeted. A detailed

list of the analyzed compounds and their limits of detection (LOD) and quantification (LOQ) is presented in Table SM2 in the Supplementary Material. Quality control measures, including replicates, calibration verification standards, and spiked samples were conducted to ensure analytical quality. Recovery standards were employed for quantification. Decachlorobiphenyl was used as a recovery standard and a set of external calibration standards solutions were prepared for the identification and quantification of target compounds. Tetrachloro-m-xylene was spiked as a surrogate for chlorinated pesticides and PCBs with an average recovery from 82±11 to 129±6% in the different matrices. 2-fluorobiphenyl and 1-chloro-octadecane were used as surrogates for PAHs and aliphatic hydrocarbons recovery, respectively (USEPA 1986, 2007a, 2007b), with an average recovery ranging from 80±4% to 88±7% for the PAHs, and from 89±3% to 139±9% for the aliphatic hydrocarbons.

All organic solvents used were SupraSolv® Grade for GC–MS and purchased from Merck KGaA (Darmstadt Germany). PAHs and aliphatic hydrocarbons standards and surrogate solutions were bought from Sigma-Aldrich, while PCBs and organochlorine pesticides standards were acquired from Agilent Technologies of Sweden AB.

Results expression and statistical analyses

Plant development in the formulated substrates and metal(oid)s uptake by tested species were assessed through three composite indicators: Tolerance Index (TI), bioconcentration factor (BCF) and uptake efficiency (UE).

The tolerance Index (TI) is used to compare biomass production among plant species by normalizing the biomass yield obtained in fiberbank substrates against that in the corresponding control substrates. It is calculated using the following formula (Diwan et al., [21]; Calvillo-Medina et al., [10]):

$$TI = \left(\frac{ABt}{ABc} \right) \quad (2)$$

where ABt is the dry weight of aerial biomass produced (g) per pot in fiberbanks substrates (treatments) and ABc is the dry weight of aerial biomass (g) per pot in peat substrates (control).

With Eq. (3) is calculated the Bioconcentration Factor (BCF) on a dry mass basis. The BCF is the parameter in phytoremediation providing information on the uptake of metal, its mobilization into the plant tissues and storage in the aerial plant parts [21]

$$BCF = \frac{\text{element concentration in the aerial biomass (mg/kg)}}{\text{element concentration in the substrate (mg/kg)}} \quad (3)$$

When the aerial biomass produced per pot was included in the calculation (Antoniadis et al. [2]), the parameter was named Uptake Efficiency (UE) and determined according to the Eq. (4).

$$UE \left(\frac{\text{mg}}{\text{KgFB}} \right) = \frac{m_{\text{element}} * m_{\text{biomass}}}{m_{\text{FB}}} \quad (4)$$

For the uptake efficiency, the mass of the target element (m_{element}) in mg, is multiplied by the dry weight (g) of the total aerial biomass produced by pot (m_{biomass}) in one cycle (or harvest) and divided by the dry mass (in grams) of fiberbank in the pot mixture (m_{FB}).

Statistical analyses included a two-way ANOVA to compare treatments and plant species, followed by Tukey Test for post hoc pairwise comparisons at a 95% confidence level. Assumptions of normality, error

independence, and homoscedasticity were verified. If these assumptions were not met, data was either logarithmically transformed or analyzed using the Kruskal–Wallis nonparametric test, with Dunn test for pairwise mean comparisons at a 95% confidence level. Changes in organic pollutant concentrations in fiberbank substrates before and after plant growth were assessed using paired samples t test. If the means differences were not normally distributed, the nonparametric Wilcoxon signed-rank test was applied at a 95% confidence level. All statistical analyses were conducted using the RStudio (R v4.1.1) package.

Results and discussion

Phytotoxicity and plant development in fiberbanks

Table 3 presents the Germination Index (GI), relative root elongation (Le/Lc), and relative seed germination (Ge/Gc) values for the selected plants seeds exposed to increasing concentrations of the fiberbank water-extract.

Table 3 Relative germination, root elongation and Germination Index values for the phytotoxicity test of tested species in fiberbanks water extracts

Species	Concentration (%) ^a	Germination (%)	Root length\ (mm)	Ge/Gc	Le/Lc	GI (%)
<i>Helianthus annuus</i>	Control	60 (14)	22.2 (3)			
	10	76 (16)	24.8 (6.8)	1.27	1.12	138
	30	75 (19)	23.2 (8.5)	1.25	1.04	138
	60	80 (16)	27 (6.6)	1.33	1.21	159
	100	68 (17)	26.6 (7.1)	1.13	1.2	135
<i>Brassica juncea</i>	Control	62 (3)	30.6 (9.3)			
	10	41 (3)	27.7 (11.9)	0.67	0.9	62
	30	65 (3)	54 (7.5)	1.05	1.76	186
	60	64 (3)	43.7 (8.8)	1.04	1.43	149
	100	71 (2)	28.3 (11.4)	1.15	0.92	107
<i>Brassica napus</i>	Control	100 (0)	58 (7)			
	10	97 (3)	70.3 (7)	0.97	1.21	118
	30	98 (3)	89.4 (7.9)	0.98	1.54	150
	60	94 (5)	88.5 (5.2)	0.94	1.52	142
	100	90 (7)	67.6 (8.1)	0.9	1.16	105
<i>Hordeum vulgare</i>	Control	93 (5)	83 (3.4)			
	10	95 (6)	101.6 (9.5)	1.03	1.23	126
	30	85 (13)	73.2 (17.6)	0.92	0.88	83
	60	80 (10)	49.8 (18.6)	1.02	1.22	126
	100	73 (5)	68.6 (14)	0.78	0.83	64
<i>Poa annua</i>	Control	90 (8)	na			
	10	95 (4)	na	0.95	na	na
	30	95 (4)	na	1.06	na	na
	60	90 (15)	na	1	na	na
	100	88 (3)	na	0.93	na	na

Results are the mean of four replicates. SD is indicated in parenthesis. na: not available

Ge: number of germinated seeds in fiberbank extract dilutions; Gc: number of germinated seeds in distilled water; Le: average value of root length in fiberbanks extracts in mm; Lc: average value of root length in the control plates (mm)

^a Concentration (%) of fiberbank 1:10 ratio water-extract dilutions: 10 to 100% (undiluted)

Root elongation in *Poa annua* could not be assessed because its weak roots prevented accurate measurement. Instead, the mean values of the relative seed's germination were considered as a toxicity indicator for this species. The GI values for *Brassica napus*, *Brassica juncea*, *Helianthus annuus*, and *Hordeum vulgare* in all fiberbank extract solutions were above the suggested threshold of 80% [20, 62], showing a low toxicity of the fiberbank material for these plant species. Moreover, the GI for these four species was mostly above 100%, indicating the potential phytostimulation properties of the fiberbanks extract. The relative germination of *Poa annua* seeds in all extract dilutions also showed values similar or above the control treatment. The slightly acidic conditions of the fiberbanks water-extracts (pH ranging from 5.1 in 100% water-extract to 6.4 in 10% dilution) or high electrical conductivity values in the more concentrated dilutions (5 to 7 mS/cm) appear not to have affected the germination and root development under the incubation settings, showing the tolerance of the robust plant species chosen. This information encouraged the formulation of plants substrates using up to 70 and 90% (volume proportion) of fiberbanks for the phytoremediation trial.

Given the pollution patterns reported for fiberbanks, and the fact that an acid pH and high soluble salts content (due to organic matter decomposition in fibrous sediments) could affect the germination process of less tolerant plant species, the observed toxicity to plants is lower than expected. This discrepancy is attributed to the aging of pollutants below the water and subsequent restricted bioavailability [1], and to the potential washing out of contaminants over time by water diffusion or advective particle transport [5, 18]. Comparatively, the concentrations of pollutants found in the sampled fiberbank from the Sundsvall Bay are not highly concerning when compared to other polluted areas with fibrous sediments. However, contamination traits vary between sites,

with some locations showing serious pollutant levels and mobility [42].

Table 4 details the mean values for total aerial biomass production and the calculated Tolerance Index for the greenhouse phytoremediation trials. The substrates containing 90% (v/v) of fiberbank showed a higher yield for both *B. juncea* and *B. napus* as compared to the treatment with 70% (v/v) fiberbank. In addition, for these species the TI values were higher in the 90% FB than in the 70% FB treatment, being tolerance values above or close to 1, indicating a healthy development of the plant species in the fiberbank substrate [1, 21]. The aerial biomass production of *Poa annua* did not show significant differences among all treatments (controls included), whereas for *Hordeum vulgare*, the biomass yield in the fiberbanks substrates was almost double compared to the control treatments with peat. The TI values for *Hordeum vulgare* and *Poa annua* were also close to or above 1 in both fiberbanks treatments. Furthermore, *Hordeum vulgare* showed a significantly higher tolerance to fiberbanks substrates than all the other tested species, being the TI around 2, which also indicates stimulating conditions for these plants' growth. Images in Figs. 2 and 3 show the aerial biomass production of tested plant species growing in substrates formulated with fiberbanks as compared to those with peat.

Although sunflower seeds germinated in the pots, the seedlings died 20 days after sowing in the 90% FB substrate, and the biomass yield was relatively low in the 70% fiberbank media. Consequently, the tolerance of sunflowers to fiberbanks substrates exhibited a different trend, with a value of 0.23 for the 70% FB treatment (suggesting stressful conditions for the plant) and null for the 90% treatment since the plants withered. The toxic effect observed in *Helianthus annuus* seedlings could be attributed to various factors, including organic or metal pollutants, as well as other conditions such as slightly acidic pH or high electrical conductivity of

Table 4 Aerial biomass production and Tolerance Index of tested plant species

Plant species	Aerial biomass (g)		TI 70%	Aerial biomass (g)		TI 90%
	70% FB	70% peat		90% FB	90% peat	
<i>H.annus</i>	0.29 (0.08)	0.95 (0.59)	0.2 (0.1)C	0	1.3 (0.23)	0 c
<i>B.napus</i>	1.08 (0.92)	2.48 (2.09)	0.3 (0.2)Cb	4.05 (2.14)	5.19 (0.55)	0.8 (0.4)Ba
<i>B.juncea</i>	0.22 (0.25)	2.39 (1.36)	0.04 (0.02)Db	2.66 (2.37)	2.97 (0.87)	1.3 (0.8)Ba
<i>H.vulgare</i>	8.31 (0.87)	3.88 (0.48)	2.2 (0.2)Aa	8.67 (1.07)	3.58 (0.22)	2.4 (0.3)Aa
<i>P.annua</i>	9.74 (0.84)	8.28 (0.27)	1.2 (0.1)Ba	8.57 (1.11)	8.99 (0.70)	0.9 (0.1)Bb

Aerial biomass yield is expressed as g/pot, on a dry weight basis. Values are the means of five replicates (pots) per treatment and by plant species. SD is indicated in parenthesis. Tolerance index (TI) was calculated considering the total aerial biomass yield produced in the 70 or 90% fiberbanks (FB) pots versus the aerial biomass yield in the 70 or 90% peat control pots. Capital letters indicate significant differences in the TI between plant species for the same treatment (p -value < 0.05). Lower letters indicate significant differences in the TI between treatments for the same plant species (p -value < 0.05)

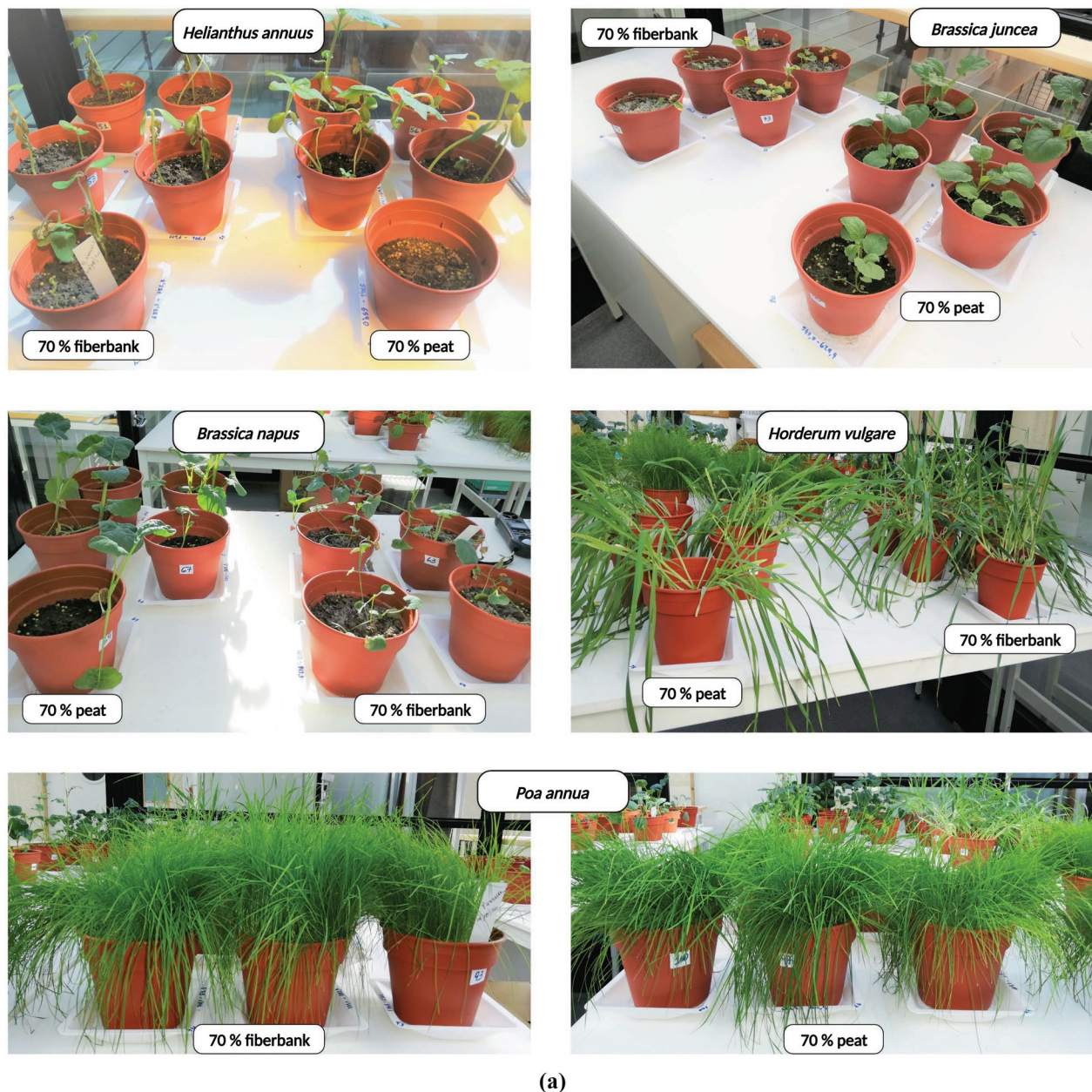


Fig. 2 Aerial biomass production of tested plant species after 75 days of growth in substrates with 70% fiberbank (v/v) or 70% peat (control)

the growing media. Nevertheless, since the acute phytotoxicity tests showed good germination index values, the low survival rate of sunflower plants may be better explained by other processes occurring in the substrate during the plant growth period. For instance, fiberbanks—composed of degrading and biologically active organic matter—can lead to unfavorable conditions in the root zone, such as low pH or poor oxygen availability. Additionally, the physical properties of the

substrate, even though optimized, may not have been suitable for proper root development for sunflowers.

Among species tested, *Hordeum vulgare* and *Poa annua* showed the best development in fiberbank substrates. Grasses from the Poaceae family, known for enduring harsh environments and rapid biomass production, are proposed to be suitable for phytoremediation [44], Rabêlo et al., [48]), emphasizing the



(b)

Fig. 3 Aerial biomass production of tested plant species after 75 days of growth in substrates with 90% fiberbank (v/v) or 90% peat (control), except for *Helianthus annuus* which exhibited withering within 20 days of growth in 90% (v/v) fiberbank substrates

importance of healthy, fast plant growth and high aerial biomass yield for efficient remediation [1, 41].

Even if perennial plants could offer higher cumulative biomass and long-term remediation potential, their use may be less practical where repeated intervention or material turnover is expected as in the context of ex-situ applications. In treatment facilities, where material

rotation, handling, or replacement may be required during the lifespan of a perennial species, annuals allow for more flexible management and integration into treatment schedules. Therefore, annual plants would offer a practical balance between effective phytoremediation and operational feasibility under managed treatment conditions. In addition, in general they establish rapidly,

grow quickly, and complete their life cycle within a single season, enabling efficient evaluation of contaminant uptake and treatment performance in time-limited treatment frameworks.

Plant development in fiberbanks substrates was investigated for phytoremediation potential, with up to 90% (volume) of the polluted material incorporated into the substrates. The physical properties of the created growing media were given special consideration, since they are relevant to provide the proper air and water conditions in the root zone when plants are grown in containers [7]. Fiberbank material showed satisfactory physical properties which resembled peat, being a low-density material with high porosity and water-holding capacity. For instance, *Brassica* species exhibited higher tolerance in substrates with a higher proportion of fiberbanks, which can be attributed to improved physical properties (Table 2) rather than to chemical toxicity of fertility status. This, in combination with a high nutrient content (Table 2), could promote potential reuse alternatives for the treated fiberbanks as a soil substitute or peat replacement for plant production, as this article's authors have proposed in (Haller et al., 2021).

Bioconcentration factor and metals uptake efficiency

The bioconcentration factor (BCF) and metals uptake efficiency (UE) parameters were calculated (Sect. “[Results expression and statistical analyses](#)”), per plant species and treatment and for nine of the ten targeted toxic metal(oid)s (As, Cd, Co, Cr, Cu, Ni, Pb, Zn and V) since mercury concentrations were originally below the limit of quantification in the collected fiberbank material (Table 2). As previously mentioned, roots could not be separated from the fiberbanks particles for analyses, thus the translocation factor could not be calculated for any of the tested plant species. Figures 4, 5, and 6 illustrates the distribution of BCF and UE values, presented as box-plots. In addition, the mean and standard deviation values for these parameters can be found in Table SM3 of the Supplementary Material.

The bioconcentration factor is commonly used to categorize plants based on their ability to accumulate metals, with values above 1 indicating accumulator plants [22]. *Brassica juncea*, *Brassica napus* and *Helianthus annuus*, showed higher affinity for As and Cd accumulation as compared to the Poaceae grasses (*Hordeum vulgare* and *Poa annua*) (Fig. 4a and c). Particularly, cadmium BCF values for these three species were above 1 for Cd, reaching up to a value close to 3 in the sunflower. Cobalt bioaccumulation factor had values below 0.4 for all tested species (Fig. 4e).

Chromium, vanadium, and lead concentration factors did not vary significantly among the tested species in the

fiberbank substrates (Figs. 5g, 6m and o), showing BCF average values of less than 0.1. In contrast, copper and zinc bioaccumulation values were above 1 for all species (Fig. 5i and q) without notable differences, except for *H. annuus* which displayed the highest BCF for copper (15 in the 70% FB treatment). Nickel accumulation showed similar trends, but with average BCF values below 1 for all species (Fig. 5k). Differences in metal accumulation between substrates (70 and 90% fiberbank) were notable for copper and zinc but were not clear for the other target metals.

Shi et al. (2023) utilized machine learning modeling to investigate the toxic metal enrichment effect of hyperaccumulator plants across 173 datasets. They found that the variability in the bioaccumulation factor is mainly influenced by the plant species family (41%) and experimental conditions (36%). The growing media (10%) and target metal properties (13%) also play a role, but to a lesser extent. This study observed that *Brassica juncea*, *Brassica napus*, and *Helianthus annuus* showed a higher affinity for some of the targeted metals accumulation (As, Cd and Cu) compared to *Hordeum vulgare* and *Poa annua*. This emphasizes the significance of plant species, particularly in *Helianthus annuus*, in determining BCF values for certain elements, supporting the findings of Shi et al. [53]. As in this study, (Benavides et al. [8]) also observed high accumulation values for cadmium uptake in both sunflower and rapeseed (*Brassica napus*) plants, which increased with higher Cd concentrations in the substrate. Also, Cd is known to be mobile in its transfer from soil to plant. Thus, this highlights the importance of the initial concentration in the substrate and the bioavailability of the target element for the phytoextraction, factors that can be highly variable between fibrous sediments polluted sites.

Limited bioavailability, natural or due to the extended aging of fiberbanks below the water, and low affinity of tested plant species could hinder the accumulation of chromium, lead and vanadium [30, 46, 53]. Strategies like organic amendments, microbe-assisted or chelate-assisted approaches could enhance phytoextraction efficiency for these elements [11]. High bioconcentration factors observed for copper and zinc in all tested species can be attributed to their high soil-to-plant transfer ratio, as they are essential micronutrients. In addition, the enrichment of these metals in the substrate due to applied fertilizer probably further contributes to their elevated concentrations in plants biomass.

In addition to hyperaccumulation traits, the harvestable biomass of candidate plants can significantly influence metal uptake efficiency (UE), also known as MER (metal extraction ratio) according to some authors (Shi et al., [53]). The aerial biomass yield of phytoremediation

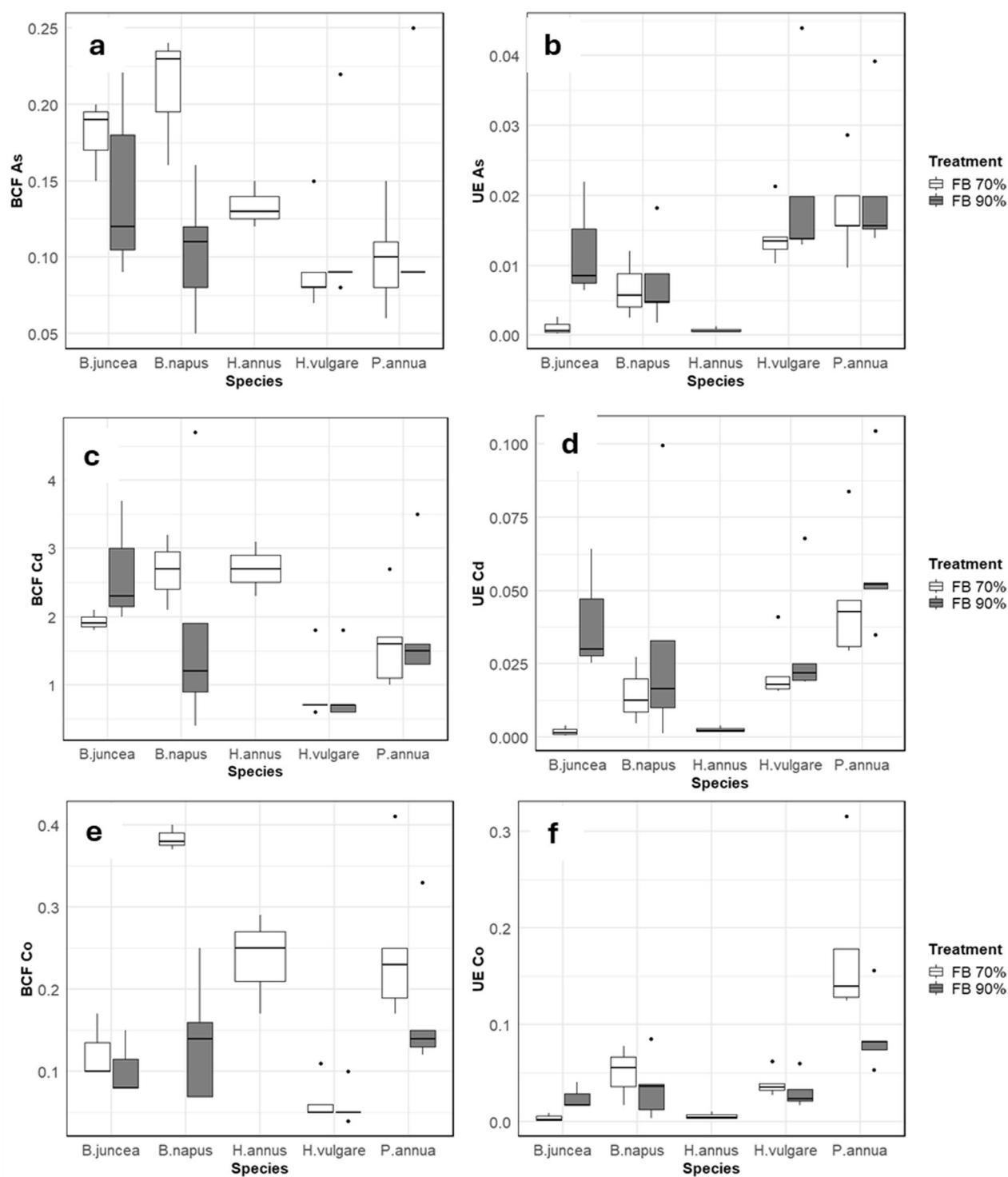


Fig. 4 a–f Data distribution for the Bioconcentration Factor (BCF) (left) and the Uptake Efficiency (UE) (right) of Arsenic (a, b), Cadmium (c, d) and Cobalt (e, f) by plant species and treatment. The horizontal line in the boxplot indicates the median and the single dot points the outliers. All means and standard deviation values of BCF and UE are detailed in Table 2 of the Supplementary Material (Table SM2)

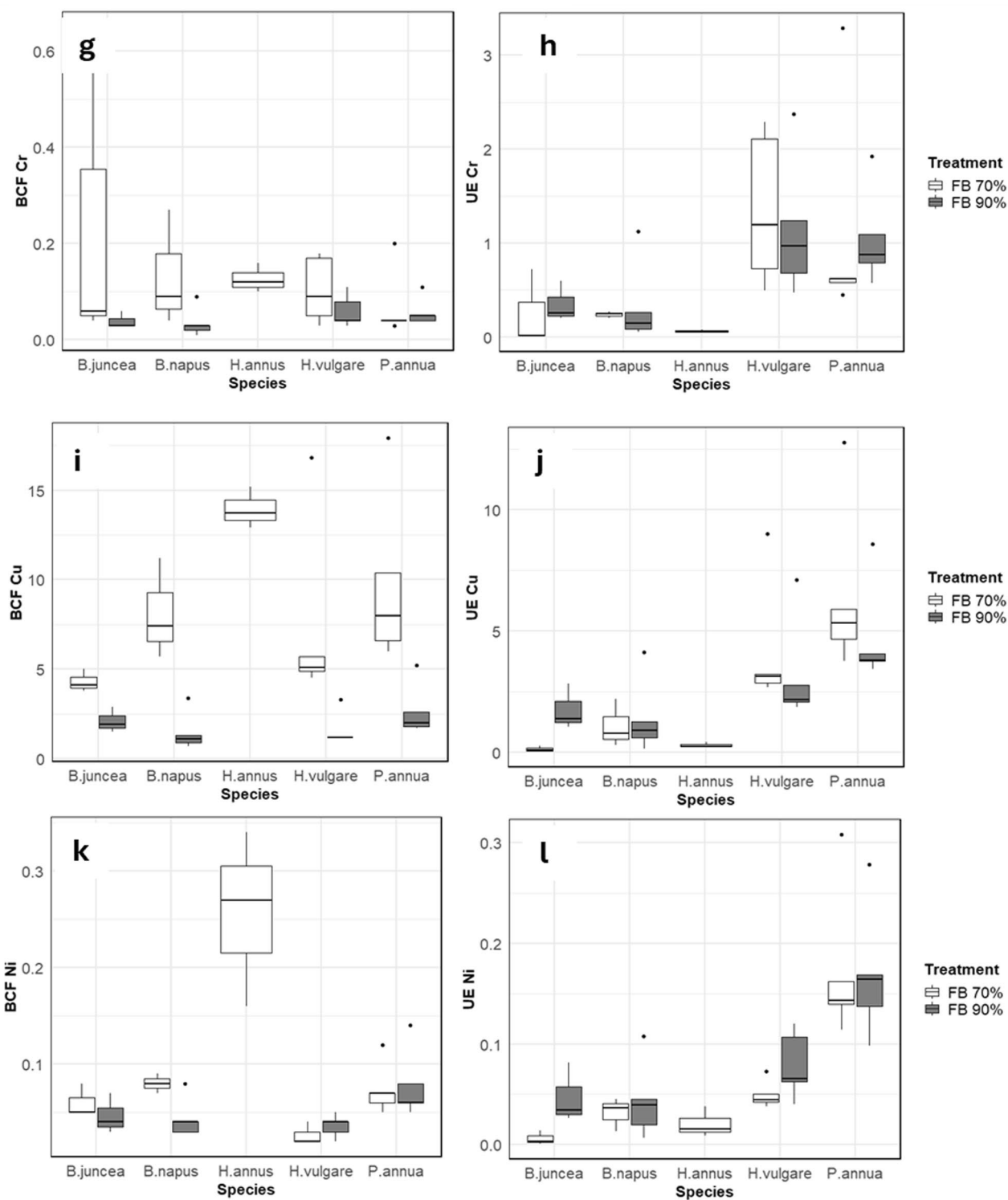


Fig. 5 g–l Data distribution for the Bioconcentration Factor (BCF) (left) and the Uptake Efficiency (UE) (right) of Chromium (g, h), Cooper (i, j) and Nickel (k, l) by plant species and treatment. The horizontal line in the boxplot indicates the median and the single dot points the outliers. All means and standard deviation values of BCF and UE are detailed in Table 2 of the Supplementary Material (Table SM2)

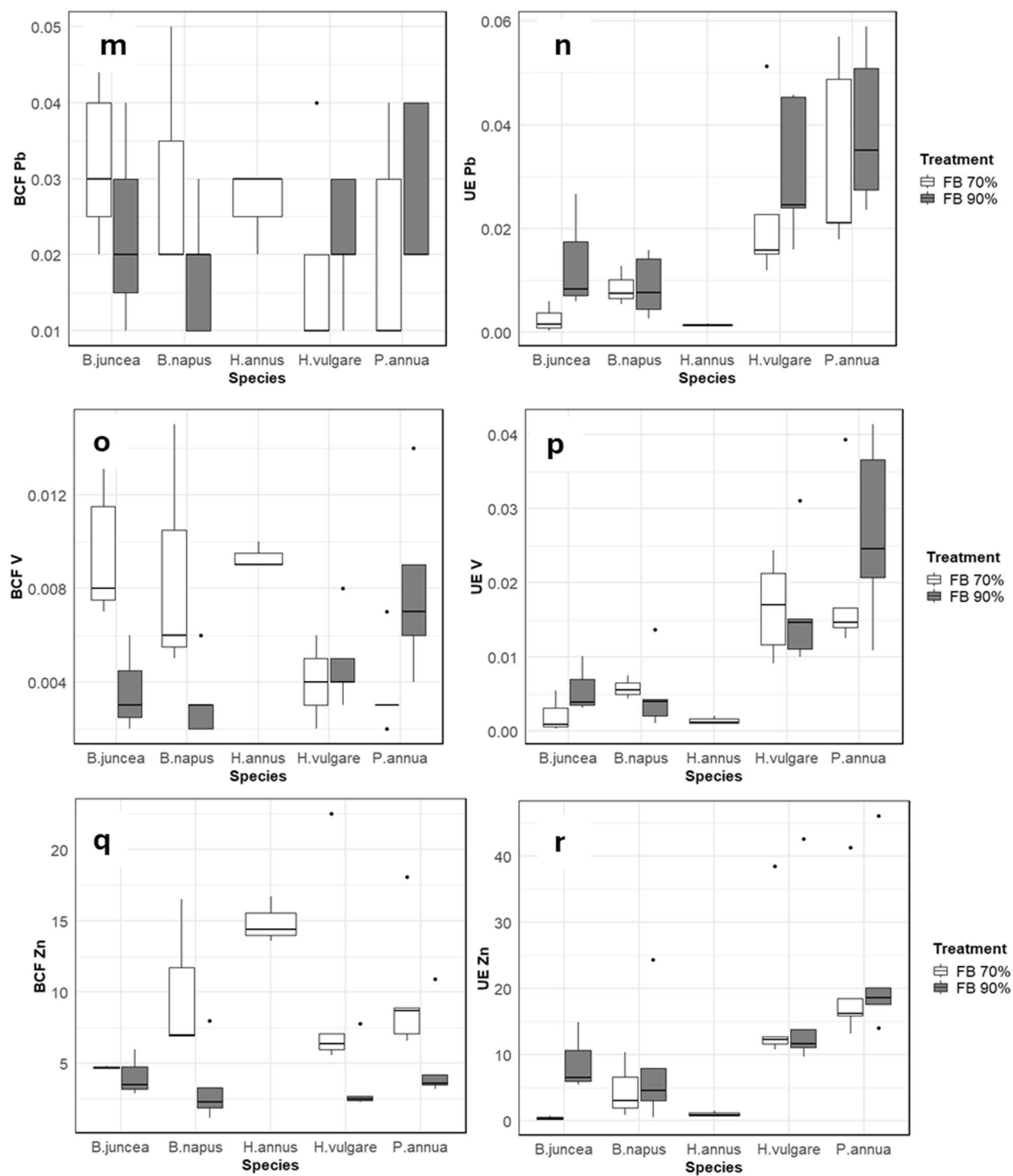


Fig. 6 m–r Data distribution for the Bioconcentration Factor (BCF) (left) and the Uptake Efficiency (UE) (right) of Lead (**m, n**), Vanadium (**o, p**) and Zinc (**q, r**) by plant species and treatment. The horizontal line in the boxplot indicates the median and the single dot points the outliers. All means and standard deviation values of BCF and UE are detailed in Table 2 of the Supplementary Material (Table SM2)

plants can be equally or even more significant than their ability to accumulate contaminating metals. This is a factor that might have been overlooked in several phytoremediation studies, as suggested by Sheoran et al. [51] and Antoniadis et al. [2]. In this study, a higher biomass yield of the tested species in fiberbank substrates, had a greater impact on the UE than the specific metal bioaccumulation traits of tested species. This trade-off between aerial biomass production and bioconcentration factor in the metal uptake efficiency, remains one of the main observations for this study. Other authors' experiments results also supported that, for some plant species, lower element concentrations in shoots can be compensated with greater biomass production for remediation effectiveness (Antoniadis et al. [2, 23]).

In Figs. 4, 5, and 6, boxplots on the right side clearly illustrate that *Poa annua* followed by *Hordeum vulgare* (which exhibited the highest aerial biomass yield) showed the highest uptake efficiency for all target metals in the fiberbank treatments, despite having lower BCF values as compared to the other tested species, as can be observed in the boxplots on the left side of Figs. 4, 5, and 6. Furthermore, no noticeable effects of the treatments (70 and 90% FB) on UE were observed, likely due to the similar aerial biomass yields of these two grasses in both substrate types (Table 4), which provides further evidence on the importance of the harvestable biomass production.

Although the Bioconcentration Factor (BCF) reflects the concentration of a contaminant in plant tissues relative to its concentration in the substrate (See Equation (iii); Sect. "Results expression and statistical analyses"), it does not account for the total mass of plant biomass produced. Therefore, a plant with a low BCF could be

judged to be not suitable for a certain metal uptake. Nevertheless, a plant with a low BCF can still be effective in phytoremediation if it produces a large amount of biomass. This is better captured by the Uptake Efficiency (UE), which combines both the contaminant concentration in the plant and the total aerial biomass to express the actual amount of contaminant removed per unit of substrate (See Equation (iv); Sect. "Results expression and statistical analyses"). As can be illustrated by a mass balance, a higher biomass yield can compensate for lower tissue concentrations, resulting in greater overall contaminant removal. Thus, evaluating phytoremediation potential based on UE provides a more realistic assessment than relying on BCF alone.

Time estimates for metal(oid)s removal from fiberbanks by *Poa annua* and *Hordeum vulgare*

An approximate estimation was made to determine the time needed for *Poa annua* and *Hordeum vulgare*, identified as the most promising plant candidates from the greenhouse experiment, to remove targeted metals from fiberbanks. Table 5 outlines the results, providing estimates of the annual uptake rate (mg metal/kg fiberbank. year) and the time (in years) required for these plants to halve the initial concentration (I_c) of the total pool of target metals in the fiberbanks material under study. It is important to note that these findings stem from experiments conducted in controlled greenhouse conditions and are based on certain assumptions: that half of the initial metal concentration in the substrate is phytoavailable, and that the aerial biomass yield and metal uptake rate remain consistent throughout the remediation period, though this may not always be the case. These factors

Table 5 Estimation of phytoextraction times for *Poa annua* and *Hordeum vulgare*

Element	I_c (mg/kg FB)	I_c $_{1/2}$ (mg/kg FB)	Uea (mg metal/kg FB)		Biomass cuts/year	Annual uptake (mg metal/kg FB.year)		Years ^a to I_c $_{1/2}$	
			<i>P. annua</i>	<i>H. vulgare</i>		<i>P. annua</i>	<i>H. vulgare</i>	<i>P. annua</i>	<i>H. vulgare</i>
As	1.01	0.51	0.02	0.02	4.9	0.08	0.09	6.6	5.9
Cd	0.37	0.19	0.04	0.03	4.9	0.22	0.13	0.9	1.4
Co	0.70	0.35	0.11	0.04	4.9	0.54	0.17	0.6	2.0
Cr	29.41	14.71	0.72	1.26	4.9	3.52	6.11	4.2	2.4
Cu	20.56	10.28	4.33	3.68	4.9	21.07	17.92	0.5	0.6
Ni	9.47	4.74	0.14	0.06	4.9	0.69	0.31	6.9	15.2
Pb	5.35	2.68	0.04	0.03	4.9	0.18	0.13	15.2	20.1
V	5.47	2.74	0.02	0.02	4.9	0.10	0.08	27.2	34.0
Zn	57.64	28.82	17.33	17.46	4.9	84.32	84.96	0.3	0.3

I_c : Average initial concentration of target metals in collected fiberbank, on a dry weight basis; I_c $_{1/2}$: Half of the average initial concentration of target metals in collected fiberbank; Uea: Uptake Efficiency, expressed as an average between results from 70% FB and 90% FB treatments for each species; FB: Fiberbank, air-dried ground < 11 mm

^a Estimation of the number of years that would take to each plant species to halve the initial concentration of metals in fiberbanks, considering assumption of phytoavailability and regular growth and uptake conditions

could potentially vary in subsequent growing cycles (Keller et al., [36]).

Based on these assumptions, the estimated time required for *Poa annua* and *Hordeum vulgare* to reduce the initial concentration of vanadium would be around 30–35 years, and for Lead, between 15 and 20 years. The annual uptake rate is estimated to be between 0.1 and 0.2 mg metal/kg fiberbank per year for these elements. The time required for As and Ni remediation may also seem impractical, but with some differences. With an annual uptake of approximately 0.1 mg of As/kg of fiberbank, it would take 6–7 years for both plant species to reduce the initial concentration of arsenic by half. On the other hand, *Poa annua* would require half the time than *Hordeum vulgare* to halve the Ni concentration, but it would still be a considerable period of approximately 7 years.

In contrast, the time required for Cd, Co, Cu, and Zn removal could sound much more feasible. Halving the concentration of these elements in the fiberbank could take less than one year for *Poa annua* and closer to 2 years for *Hordeum vulgare*. Even though the annual uptake rate of Cr is high for both plant species (3.52 and 6.11 mg Cr/kg fiberbank for *Poa annua* and *Hordeum vulgare*, respectively), the estimated time to halve the concentration of this element would range from 2.5 to 4 years, probably due to the fact that Cr initial concentration in the substrates is significantly higher than that of the other elements (Table 2).

A crucial aspect regarding the efficiency and sustainability of phytoremediation strategies is the time required to achieve the remediation goal, which can be considered a potential drawback of this biotechnology application. Remediation time is influenced not only by the bioconcentration factor and aerial biomass yield of the candidate plant but also by factors such as the possibility of multiple harvests per season and a stable uptake rate and growth. This is reflected in the model developed by Shi et al. [52], which suggests that when predicting remediation times, plant family is the most important feature, followed by experimental conditions, metal properties, and soil properties. However, further research is needed to fully understand this important aspect in phytoremediation.

In this study, the estimated remediation times for *Poa annua* and *Hordeum vulgare* could be impacted by the bioavailability of target metals in the polluted material, a relevant aspect not considered in the model by Shi et al. [52], as well as the initial concentration of elements, such as the case of chromium in our study. High concentrations of toxic metals in more polluted fibrous sediments can significantly affect the overall remediation time and limit the effectiveness of phytoremediation.

Organic pollutants degradation

The fiberbank material collected from Sundsvall's Bay primarily contained polycyclic aromatic hydrocarbons and linear hydrocarbons, while targeted polychlorinated biphenyls and chlorinated pesticides were below quantification limits. To assess the potential degradation of these pollutants during the plant growth trial, the concentrations of aromatic and linear hydrocarbons were measured in fiberbank-based substrates (70 and 90% FB) both before and after plant growth. The quantified hydrocarbons were grouped by molecular size: PAHs by the number of aromatic rings, and alkanes by the number of carbon atoms in their chains. Table 6 presents the results by plant species and treatment.

Although some hydrocarbon groups showed statistically significant differences in concentrations before and after plant growth ($p < 0.05$), the actual magnitude of these changes was relatively small. Notably, where significant changes did occur, they generally reflected an increase rather than a decrease in hydrocarbons concentrations after plant growth. For instance, significant increases in PAHs concentrations with 4–6 aromatic rings were observed across all plant species and both fiberbank treatments (70 and 90% FB). For alkanes, significant changes were found only in the 90% FB treatment, specifically within the C12–C16 and C18–C22 carbon chain groups. However, when considering the total concentration of the 16 priority PAHs or the combined total of PAHs and alkanes, no statistically significant differences were observed before and after the plant treatment.

For hydrocarbon compounds, the primary phytoremediation mechanism relies on rhizodegradation, which involves the degradation of hydrocarbons via the microorganisms living in the rhizosphere (i.e. the narrow region of substrate that surrounds and is directly influenced by plant roots), stimulated by the supply of energy and nutrients from plant root exudates [28]. However, this process requires microbial strains or species with the ability to use the contaminants as a carbon or energy source, in combination with a minimum available concentration of the pollutant that could trigger the degradation process, and enough time for the process to develop [27, 40]. For instance, in a trial for the phytoremediation of a soil co-contaminated with PAHs and toxic metal(oid)s using alfalfa and black nightshade, [11] observed that PAHs removal percentage for alfalfa was double after 90 days of plant growing with respect to the removal after 30 days. It is possible then that, in this study, the short experimental time (75 days) for hydrocarbon degrading strains adaptation, and the low initial concentration or availability of the target compounds (given the organic nature and aging of the fiberbanks material) may have

Table 6 Organics pollutants concentration in fiberbanks substrates before and after plant growth

	70% FB					90% FB					
	Initial		Final			Initial		Final			
			<i>B. napus</i>	<i>B. juncea</i>	<i>H. vulgare</i>	<i>P. annua</i>			<i>B. napus</i>	<i>B. juncea</i>	<i>H. vulgare</i>
Sum PAHs 2–3 rings (mg kg ⁻¹)	1.41 ± 0.16	1.48 ± 0.43	1.39 ± 0.5	1.67 ± 0.33	1.37 ± 0.28	5.4 ± 0.78	4.99 ± 1.08	4.74 ± 1.42	7.62 ± 1.44	5.66 ± 1.85	
Sum PAHs 4–6 rings (mg kg ⁻¹)	0.07 ± 0.02	0.12 ± 0.02*	0.14 ± 0.03*	0.16 ± 0.04*	0.12 ± 0.04*	0.58 ± 0.22	0.68 ± 0.14*	0.7 ± 0.11*	0.63 ± 0.16*	0.82 ± 0.13*	
Sum 16 PAHs (mg kg ⁻¹)	1.47 ± 0.18	1.59 ± 0.45	1.52 ± 0.51	1.83 ± 0.35	1.49 ± 0.31	5.97 ± 0.97	5.67 ± 1.2	5.44 ± 1.48	8.24 ± 1.58	6.47 ± 1.96	
Alkanes C12-C16 (mg kg ⁻¹)	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	1.5 ± 0.16	1.63 ± 0.2*	1.59 ± 0.13*	1.85 ± 0.09*	1.77 ± 0.21*	
Alkanes C18-C22 (mg kg ⁻¹)	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.55 ± 0.07	0.59 ± 0.04*	0.61 ± 0.05*	0.6 ± 0.07*	0.74 ± 0.1*	
Sum PAHs + Alkanes (mg kg ⁻¹)	1.47 ± 0.18	1.59 ± 0.45	1.52 ± 0.51	1.83 ± 0.35	1.49 ± 0.31	8.02 ± 1.18	7.88 ± 1.37	7.63 ± 1.57	10.67 ± 1.69	8.98 ± 2.25	

Mean and standard deviation values are reported of four replicates for the initial concentrations and five replicates for final concentrations. The individual compounds in each group are listed in Table SM2 of the Supplementary Material

PAHs: Polycyclic Aromatic Hydrocarbons; LOQ: Limit of Quantification

* Significant differences (95% confidence level) between the initial and residual concentration in the substrates after 75 days of plant growth

restricted hydrocarbons degradation. Longer experimental times in future trials would allow a better assessment of the rhizodegradation potential for organic pollutants removal in fiberbanks.

The slight positive differences observed in the concentrations of target hydrocarbons before and after plant growth could largely be attributed to common fluctuations inherent in analytical methods, especially given the heterogeneous nature of the substrates studied. Soil and substrate matrices often present spatial variability in contaminant distribution, which can lead to variability in sample extraction and analysis. This is stressed in materials like fibrous sediments. Moreover, during the plant growth period, some degree of desorption of hydrocarbons from the fiberbanks may occur, influenced by root activity and changes in substrate chemistry. Root exudates, particularly organic acids such as citric and oxalic acid, have been demonstrated to enhance the desorption and bioavailability of aged polycyclic aromatic hydrocarbons (PAHs), facilitating their mobilization from tightly bound soil fractions [26]. On the other hand, some phytogenic compounds could be not easily distinguished from the target pollutants with the available analytical methods, because of their structural similarities, leading to an overestimation of the quantified results [27].

Conclusions

Remediating fibrous sediments presents challenges due to their complex and not fully understood nature. These sediments are characterized by substantial organic matter undergoing degradation, leading to gradual changes in their physical and chemical properties. In addition, toxic metal(oid)s and organic pollutants contamination patterns vary across various sites. In this study, the phytoremediation potential for fiberbanks material was successfully explored. Despite initial concerns about the properties of these sediments hindering the formulation of proper plants growing media, fiberbank material exhibited favorable physical properties and a certain degree of fertility that supported containerized plant growth. Additionally, all tested plant seeds were able to tolerate their expected toxicity.

The Poaceae species, *H. vulgare* and *P. annua*, showed the better tolerance to the fiberbanks substrates and a superior aerial biomass development. Zn, Cu and Cr were most effectively taken up by these plants, while the uptake of Co and Ni was lower. On the other hand, As, Cd, Pb and V phytoextraction was not significant, highlighting the importance of target elements bioavailability. Also, these two species had the highest metal uptake efficiency, despite lower bioconcentration factors for most of the target elements. The impact of

aerial biomass production on metal uptake efficiency is often overlooked and is one of the key outputs of this study. The limited degradation of organic pollutants observed during the plant growth period was likely due to their low initial availability in the substrate and the testing time. A longer trial may be needed to activate microbial or plant-based degradation mechanisms. On the other hand, amendments like surfactants, could improve bioavailability and stimulate microbial activity for enhancing organic pollutants breakdown.

Phytoremediation, whether used alone or alongside other methods, shows promise for the ex situ treatment of fibrous sediments. It offers advantages, such as low costs, zero emissions, and the potential to reuse harvested biomass for energy, biochar production, or metal recovery. However, a thorough understanding of pollution patterns and aged contaminants availability is crucial to design effective remediation strategies for these sediments in an after-dredging scenario.

Abbreviations

AP	Air porosity
ASE	Accelerated solvent extraction
BCF	Bioconcentration factor
DDTs	Dichlorodiphenyltrichloroethanes
EC	Electrical conductivity
FBs	Fiberbanks
GC-MS	Gas chromatography-mass spectrometry
GI	Germination index
HCB	Hexachlorobenzene
ICP-AES	Inductively coupled plasma-atomic emission spectroscopy
ICP-MS	Inductively coupled plasma-mass spectrometry
LOD	Limit of detection
LOQ	Limit of quantification
OM	Organic matter
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
POPs	Persistent organic pollutants
TI	Tolerance index
TN	Total nitrogen
TP	Total porosity
UE	Uptake efficiency
VOCs	Volatile organic compounds
WRC	Water retention capacity

Supplementary Information

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Supplementary Material 1.

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GLP: Conceptualization, Methodology, Investigation, Visualization, Formal analysis, Writing – original draft, Writing – review & editing. GD: Investigation, Methodology, Validation, Writing – review & editing. AJ: Conceptualization, Methodology, Validation, Supervision, Writing – review & editing. HH: Conceptualization, Methodology, Validation, Supervision, Writing – review &

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Data availability

No datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate

As authors, we declare that our manuscript is original, unpublished, and not under simultaneous consideration elsewhere. We commit to transparency in re-using material, proper citation, clear and honest data presentation, and not splitting one study into multiple submissions. We avoided excessive self-citation and untrue statements about others. Correct authorship was ensured at submission, with detailed explanations for any changes during revision. We respect third-party rights, including copyright and moral rights.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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