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SEDIMENT CHALLENGES AND OPPORTUNITIES

Recovery and environmental recycling of sediments: the experience of CNR-IRET Pisa

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Abstract

Purpose The main results of the experience of CNR-IRET Pisa regarding sediment recovery and recycling are reported.
Methods and results In the AGRIPORT project, saline and brackish sediments were mixed with agronomic soil and underwent phytoremediation. After two years, heavy metals and hydrocarbons decreased, and the improvement of chemical and biological properties created a "functional soil" for further applications. Both phytoremediated sediments were refined through landfarming in the CLEANSED and HORTISED projects and applied for civil and agricultural uses. The landfarming process further reduced the organic contaminants in both sediments. Then, in CLEANSED, nursery plants performed similarly in brackish sediment-based substrates as in alluvial soil (control) (33% and 50%). In HORTISED, horticultural plants, grown on substrates with peat and remediated saline sediments (50%), had a yield, number, weight, and fruit quality comparable with those grown on peat. In the "Fondazione Cassa di Risparmio di Pistoia e Pescia" project, the decontaminated saline sediments were successfully co-composted with *Posidonia oceanica* and reused as nursery growth substrate. Another two European LIFE projects are still in progress. The SUBSED project aims to confirm the suitability of saline-remediated sediments after landfarming as an alternative substrate to peat and coconut fiber for fruit, flowering, and non-food crops. The AGRISED project aims to recover brackish sediments through a co-composting process with green waste to produce an innovative substrate for the cultivation of ornamental plants.
Conclusions The projects confer environmental, economic, and social values to sediments, through their eco-sustainable recovery and use in different sectors.

Keywords Compost · Growing media · Horticulture · Landfarming · Nursery · Phytoremediation

1 Introduction

In Europe, about 200 million m^3 of sediments are dredged from ports and waterways every year, in order to maintain shipping traffic efficiency. Although EU waste policy encourages the application of the circular economy to waste materials, through the production of high-quality resources (EU 2008), there are legislative limitations for the reuse of dredged sediments in agriculture sector (EU 2019). In particular, the presence of a high level of contaminants (heavy metals and hydrocarbons) makes dredged sediment a waste material, with expensive costs for their disposal. The classification of nutrient-rich recycled sediments as fertilizer would be desirable in the new EU regulations.

Before using dredged sediments for different applications, such as nursery and horticulture, the decontamination of these matrices is needed, according to local legislation. Amongst bioremediation technologies, phytoremediation and landfarming are both successfully applied to reduce inorganic and organic contaminants as well as to improve the biological activity in polluted saline and brackish sediments (Masciandaro et al. 2014; Macci et al. 2021). In addition, the composting of sediment with other wastes,such

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as green residues, can facilitate recycling by creating a pathogen-free organic amendment and substrate for non-food agronomic purposes (Onwosi et al. 2017; Peruzzi et al. 2021; Macci et al. 2021). After the application of proper remediation techniques, remediated sediment can be included in the circular economy perspective through their recycle in nursery and horticulture sectors, thanks to the positive results achieved as component in growing media. In fact, the suitability of remediated sediments as a substrate component has been demonstrated for strawberry (Tozzi et al. 2020, 2021), pomegranate (Martínez-Nicolás et al. 2021), and non-food agricultural crops (Mattei et al. 2017; Ugolini et al. 2017). In addition, the accumulation of inorganic and organic contaminants does not occur in strawberry and pomegranate fruits, grown on a substrate based on remediated sediment (Tozzi et al. 2020, 2021; Martínez-Nicolás et al. 2021), thus demonstrating the safety of using these matrices for food crop cultivation. The use of remediated sediment as a component in growing media could replace nonrenewable materials, such as peat. Specifically, the growing substrate, composed of remediated sediments, needs to be in compliance with the legal thresholds as well as to meet plant requirements, i.e., providing an appropriate environment for root development, for efficient plant nutrient supply and pathogen-free conditions (Barret et al. 2016). The application of dredged sediment for nursery and horticultural purpose contributes to improve such valueless waste as well as to turn it into a valuable raw material. The aim of this work is to demonstrate, through the experience of CNR-IRET, the suitability of the remediation of brackish and saline sediment with eco-sustainable and low-cost technologies (phytoremediation, landfarming, co-composting) as well as the safe recycling of remediated sediments in the nursery, horticultural and civil sectors.

2 Materials and methods

The experimental layouts for each presented project are reported in Table 1. The sediments, composts, and substrates were monitored and characterized through chemical and physical analysis. The bulk density (BD) was evaluated by means of the weight of a dry sample at a known volume (ISO 2017). Electrical conductivity (EC) and pH were measured in the water extract (1:5, *v/v*), using selective electrodes (EC: Conmet 2, Hanna Instruments Italia; pH: Titroprocessor 672, Methron Switzerland). Cation exchange capacity (CEC) was determined according to the ISO 11260 method (ISO 1994), using barium chloride solution. N-NH_3 and N-NO_3 were measured in the water extract with a selective electrode (Sevenmulti Mettler Toledo). Total organic carbon (TOC) and total nitrogen (TN) were mainly determined by dry combustion with a RC-412 multiphase and FP-528 protein/nitrogen determinator (LECO corporation), respectively. The total microbial activity was measured using fluorogenic methylumbelliferyl (MUF)-substrates (Marx et al. 2001; Vepsäläinen et al. 2001). Total metals (Zn, Cd, Ni, Cu, Cr, Pb) and organic contaminants (C>12, PAHs and PCBs) were determined by ICP–OES (Peruzzi et al. 2020, 2021) and gas chromatography–mass spectrometry (USEPA 1995, 1997, 2007), respectively. Ecotoxicological tests were performed by means of germination tests using *Lepidium sativum* seeds, following Hoekstra et al. (2002). For further details, consult the relative studies of each project (Table 1).

Statistical analysis was done using the STATISTICA 7.0 (StatSoft Inc., Tulsa, Oklahoma, USA) through the analysis of variance (one-way ANOVA), following by the HSD Tukey's test ($P < 0.05$).

3 Results and discussion

The decontamination of sediments is required before their reuse and the application of phytoremediation is an economically sustainable treatment (Masciandaro et al. 2014). In the AGRIPORT project, the effectiveness of phytoremediation in recovering saline and brackish sediments was demonstrated. The process led to a decrease in heavy metals (−20%) and total petroleum hydrocarbon (−50%) concentrations as well as an improvement in chemical nutritional properties and in microbial activity. The bioremediation technique produced a "technosoil" for several environmental purposes, e.g. plant growth substrate (Doni et al. 2013; Masciandaro et al. 2014; Ugolini et al. 2017). The application of further treatments on phytoremediated sediment reduces the pollutant concentrations and improves the substrate properties. The phytoremediated brackish sediment underwent 3 months of landfarming in the CLEANSED project, creating a homogenized substrate with increased biological activity (+30%) and a reduction in organic contamination (−30%). This matrix was suitable for reuse in a nursery, in compliance with Italian regulations for agronomic substrates (D.lgs. 75/2010), with the exception of total organic carbon (< 4%) (Macci et al. 2021). To increase the percentage of the total organic carbon, the matrix was mixed with an agronomic soil, resulting suitable as a growing medium. In fact, *Photinia x fraseri* and *E. macrophylla* showed the same growth parameter values as the control (agronomic soil alone), while *V. tinus* grew more in substrates based on 33% and 50% of treated brackish sediments (Ugolini et al. 2017). In addition, in the CLEANSED project, landfarming was also evaluated as a biological strategy to directly remediate the brackish sediment, eliminate organic pollution, and reuse it in the civil sector. After 5 months of landfarming, there was a reduction of 40% and 60% in water content and organic contamination, respectively. The remediated sediments were mixed with 15% of lime to reach the optimal water content and used for the construction of a cycle track in

Table 1 Experimental layout details for each project

LIFE project	Experimental layout	References
AGRIPORT (ECO/08/239065) Agricultural reuse of polluted dredged sediment	Brackish and saline dredged sediments were pre-conditioned by adding an agronomic soil (30 % *v/v*). The following plant treatments were tested for two years: *Paspalum vaginatum*, *Phragmites australis*, *Spartium Junceum*, *P. vaginatum*, *Nerium oleander*, *P. vaginatum*, *Tamarix gallica*, *P. vaginatum*, and unplanted control.	Doni et al. (2013) Masciandaro et al. (2014)
CLEANSED (LIFE12 ENV/IT/000652) Innovative integrated methodology for the use of decontaminated river sediments in plant nursing and road building	Landfarming was carried out on phytoremediated backish sediments from the AGRIPORT project for 3 months. Then, three plant species (*Viburnus tinus*, *Eleagnus macrophylla*, *Photinia x fraseri var.* Red Robin) were grown on sediment (100%) and substrate composed of sediment and agronomic soil, in a ratio of 50% and 33%. Fresh brackish sediments underwent landfarming for 5 months and were mixed with lime (15%) for road construction.	Doni et al. (2013) Ugolini et al. (2017) Macci et al. (2021)
HORTISED (LIFE14 ENV/IT/000113) Demonstration of the suitability of dredged remediated sediment for safe and sustainable horticulture production	Phytoremediated saline sediment (AGRIPORT) underwent landfarming for 3 months. Then, pomegranate trees, strawberry, and lettuce were placed on growing media made up of (*v:v*) 100% remediated sediment (S100), 50% remediated sediment and 50% peat (S50) and 100% peat as control (S0).	Tozzi et al. (2020, 2021) Martínez-Nicolás et al. (2021)
Fondazione Cassa di Risparmio di Pistoia e Pescia	Saline sediments, previously phytoremediated (Agriport) were co-composted with *Posidonia oceanica* residues for six months. Three mixtures were tested: 20% *P. oceanica* residues + 80% green residues (M1); 20% *P. oceanica* residues + 60% green residues + 20% of decontaminated sediments (M2); 10% *P. oceanica* residues + 80% green residues + 10% decontaminated sediments (M3). Posidonia-based compost (20% of *P. oceanica* residues and 80% green residues) and decontaminated sediments were used as a component of growing-media (70:30, *v:v*) for *Viburnum tinus* cultivation. The tested substrate properties and the plant performance were compared to a traditional peat.	Peruzzi et al. (2020) Peruzzi et al. (2021)
SUBSED (LIFE17 ENV/IT/000347) Sustainable substrates for agriculture from dredged remediated marine sediment: from ports to pots	Based on the HORTISED experience, landfarming was carried out on phytoremediated saline sediments, derived from the AGRIPORT project, for 3 months. Treated sediments were used as agronomic substrate for nursery plants (olive and citrus), ornamental plants (protea, calla, laurel), and food plants (basil, blueberry, wild strawberry, and citrus).	Under preparation
AGRISED (LIFE17 ENV/IT/269) Use of dredged sediments for creating innovative growing media and technosols for plant nursery and soil rehabilitation	Brackish sediments (S) and green waste (GW) biomass (grass, corn cob, wood chips, and dry leaves) were co-composted for about 8 (Czech Republic) and 6 (Italy) months, at the following ratios (*w:w*) 3S:1GW (A), 1S:1GW (B), and 1S:3GW (C). The Czech composts are being tested as substrate and component of growing media for *Viburnum tinus* and *Photinia x fraseri* as follows: 60% peatmoss – pumice (1:1) + 40% 1S:3GW compost; 60% pumice (1:1) + 40% 1S:1GW compost; 60% peatmoss – pumice (1:1) + 40% 3S:1GW compost; 1S:3G compost; 1S:1G compost; 3S:1G compost; peatmoss – pumice (1:1) as control.	Under preparation

Table 2 Results of landfarming carried out on saline phytoremediated sediment in HORTISED and SUBSED projects

		HORTISED		SUBSED		
		Ti	*Tf*	*Ti*	*Tf*	IT legislation D.Lgs.75/2010
BD	*g cm*$^{-3}$	1.69b	1.48a	1.49b	1.19a	≤ 0.95
EC	*dS m*$^{-1}$	0.45a	0.30b	0.26a	0.14b	≤ 1.0
pH		8.53a	8.5a	7.5a	7.4a	4.5-8.5
Cu	*mg kg*$^{-1}$	36.3a	34.3a	45a	49a	≤ 230
Zn	*mg kg*$^{-1}$	231a	248a	151a	146a	≤ 500
Ni	*mg kg*$^{-1}$	35.1a	34.6a	38a	38a	≤ 100
Pb	*mg kg*$^{-1}$	36.0a	35.2a	39a	37a	≤ 140
Cr	*mg kg*$^{-1}$	54.9a	54.3a	60a	50a	≤ 150
TN	%	0.18a	0.13b	0.11a	0.11a	≤2.5
TOC	%	2.30a	1.97b	1.35a	1.38a	≥ 4
CEC	*meq 100g*$^{-1}$	14.5a	18.3b	12.6a	12.6a	

Data are means of three replicates and letters indicate statistical differences between time of samplings (one-way ANOVA)

BD, bulk density; *EC*, electrical conductivity; *TOC*, total organic carbon; *TN*, total nitrogen; *CEC*, cation exchange capacity; *BUT*, butyrate activity

Pisa (Italy) along the Navicelli canal, from which the sediments were dredged. The landfarming strategy was also applied to phytoremediated saline sediment in the HORTISED and in SUBSED projects for 3 months, to confirm the suitability of the sediments as substrate for several plants, after phytoremediation and landfarming treatments. After 3 months of the landfarming, the BD and EC reduced in both projects, indicating, respectively, an increase of aerobic conditions as well as the salt leaching, due to the turning activity and rainfalls, as seen for the landfarming of phytoremediated brackish sediments (Macci et al. 2021). The better aerobic conditions enhanced microbial activities, leading to the greatly reduction of hydrocarbons (C>12) to 207 and 100 mg kg^{-1} in the HORTISED and SUBSED projects, respectively, thus creating a substrate with suitable properties for sediment reuse in horticulture (D.lgs. 75/2010). As expected, no variation in heavy metal concentrations was observed, showing values in line with Italian legislation (Table 2). However, at the end of landfarming in both projects, only TOC and BD showed lower and higher values, respectively, than the legal thresholds (D.lgs. 75/2010) (Table 2). The mixing of remediated saline

Table 3 Chemical and physical characterization of nursery substrates composed of treated saline sediment in SUBSED project

		Substrates							
		L1	*L2*	*L3*	*L4*	*L5*	*L6*	*L7*	IT legislation D.Lgs.75/2010 Mixed media
BD	*g cm*$^{-3}$	0.31a	0.54c	0.61d	0.49c	0.63d	0.45b	0.68e	≤ 0.95
EC	*dS m*$^{-1}$	0.15a	0.41c	0.36c	0.41c	0.40c	0.21b	0.19b	≤ 1.0
pH		4.6a	6.5b	6.7c	7.4d	7.7e	7.9ef	8.0f	4.5-8.5
TN	%	0.64e	0.18b	0.14a	0.21c	0.17b	0.33d	0.18b	≤2.5
TOC	%	7.96d	5.41b	3.52a	7.41d	5.68b	10.85e	4.86b	≥ 4
CEC	*meq 100g*$^{-1}$	60.9a	46.2d	20.1a	34.3c	27.5b	41.3d	26.3b	
Cd	*mg kg*$^{-1}$	<lq	<lq	<lq	<lq	<lq	<lq	<lq	<1.5
Cu	*mg kg*$^{-1}$	12.1a	37.6bc	40.8cd	33.3b	39.4c	38.1c	45.2d	≤ 230
Zn	*mg kg*$^{-1}$	18.1a	136.7bc	150.4c	114.6b	143.0bc	133.6bc	181.3d	≤ 500
Ni	*mg kg*$^{-1}$	6.5a	36.1cd	37.6d	30.0b	37.0d	34.2c	38.6d	≤ 100
Pb	*mg kg*$^{-1}$	20.6a	40.1cd	43.1c	34.0b	43.1d	38.1	47.4e	≤ 140
Cr	*mg kg*$^{-1}$	5.2a	44.7c	40.7c	32.3b	42.9c	41.4c	41.2c	≤ 150

Data are means of three replicates and letters indicated statistical differences between substrates (one-way ANOVA)

L1, 60% peat + 40% pumice; *L2*, 45% peat + 30% pumice + 25% sediment; *L3*, 30% peat +20% pumice + 50% sediment; *L4*, 45% coconut + 30% pumice + 25% sediment; *L5*, 30% coconut + 20% pumice + 50% sediment; *L6*, 45% fiber + 30% pumice + 25% sediment; *L7*, 30% fiber + 20% pumice + 50% sediment; *BD*, bulk density; *EC*, electrical conductivity; *TOC*, total organic carbon; *TN*, total nitrogen; *CEC*, cation exchange capacity; *lq*, limit of quantification

Table 4 Chemical and physical properties of Czech (CZ) and Italian (IT) composts in AGRISED project

		CZ Compost			**IT Compost**			**CZ legislation** Decree No. 257/2009	**IT legislation** D.Lgs.75/2010
		A	*B*	*C*	*A*	*B*	*C*	Sediment reuse in agriculture	Growth substrate
pH	%	8.12	8.12	8.18	7.2	7.1	7.0		4.4-8.5
BD	*g cm^{-3}*	1.00	0.81	0.75	0.53	0.66	0.87		≤0.95
EC	*dS m^{-1}*	0.86	0.78	0.75	2.99	2.16	1.41		≤1
TOC	%	3.02	3.04	5.04	1.34	4.97	9.35		≥4
TN	%	0.26	0.31	0.50	0.13	0.30	0.61		≤2.5
PAH	*mg kg^{-1}*	0.45	0.41	0.40				≤6	
PCB	*mg kg^{-1}*	<0.01	<0.01	<0.01				≤0.2	
Cd	*mg kg^{-1}*	0.25	0.22	0.3	0.38	0.30	0.23	<2	<1,5
Cu	*mg kg^{-1}*	58.2	56	52.9	33	29	21	<100	<230
Hg	*mg kg^{-1}*	<0.1	<0.1	0.12	0.05	0.04	0.05	<1	<1,5
Ni	*mg kg^{-1}*	29.2	29.1	28.4	32	30	28	<100	<100
Pb	*mg kg^{-1}*	18.9	18.3	18.3	23	22	20	<140	<140
Zn	*mg kg^{-1}*	87.4	86.9	96.5	96	105	99	<500	<500
Cr	*mg kg^{-1}*	25.1	23.5	23	30	36	29	<2	<100

Data are means of three replicates

A, 3S:1GW; *B*, 1S:1GW; *C*, 1S:3GW; *BD*, bulk density; *EC*, electrical conductivity; *TOC*, total organic carbon; *TN*, total nitrogen; *PAH*, polycyclic aromatic hydrocarbons; *PCB*, polychlorinated biphenyls

sediments with a source of organic matter rich in carbon and light in structure was needed to fall within the legal limits. Specifically, in the HORTISED project, the substrate composed of remediated sediment and peat (1:1 *v:v*), resulting suitable for the cultivation of sensitive plants without affecting the fruity quality, such as strawberry (Tozzi et al. 2020, 2021) and pomegranate (Martínez-Nicolás et al. 2021). In the SUBSED project, different substrates were arranged, using not only peat but also wood fiber and coconut, in order to broaden the applications in several cultures, i.e. fruit trees (olive and citrus), ornamental plants (protea, calla, laurel), and food plants (basil, blueberry, wild strawberry, and citrus). The addition of other organic substrates to sediments leads to a reduction in BD and an increase in TOC, thus falling within the Italian legislation limits, as seen also for BD, EC, pH, and heavy metals (D.lgs. 75/2010). The plant trials for the SUBSED project are still in progress and an example of tested substrates is reported in Table 3.

Composting is another biological method of waste management that degrades and converts degradable materials into humic-rich and sterilized products, thanks to microorganism activities (Ayilara et al. 2020). The suitability of phytoremediated sediment to be composted has been demonstrated in “Fondazione Cassa di Risparmio di Pistoia e Pescia” project. Particularly, Peruzzi et al. (2020) highlighted the co-composting efficiency of saline-remediated sediment with *P. oceanica* residues, reaching the stability and maturity of the three obtained composts (M1, M2, M3), through the enrichment in humic carbon, the high germination index, and the reduced electrical conductivity. The final products showed had chemical and physical

Table 5 Chemical and physical characterization of substrates composed of Czech composts in the AGRISED project

		Substrates							IT legislation D.Lgs.75/2010
		S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	Mixed media
pH		4.8a	6.4b	7.0bc	7.0bc	7.5c	7.6c	6.9bc	4.5-8.5
BD	*g cm^{-3}*	0.3a	0.3a	0.6bc	0.6b	0.7cd	0.8cd	1.0d	≤0.95
EC	*dS m^{-1}*	0.3a	0.5a	1.0b	1.0b	1.6c	1.5c	1.6c	≤1
TOC	%	13g	10f	7.7e	3.7c	6.6d	4.5b	2.4a	≥4
TN	%	0.4b	0.5c	0.5c	0.3a	0.7d	0.4b	0.3a	≤2.5
CEC	*meq 100g^{-1}*	42.6bc	45.5c	38ac	26a	45.7c	44bc	30.2ab	

Data are means of three replicates and letters indicated statistical differences between substrates (one-way ANOVA)

S1, peat moss – pumice (1:1) as control; *S2*, 60% peat moss – pumice (1:1) + 40% compost (1S:3GW); *S3*, 60% peat moss – pumice (1:1) + 40% compost (1S:1GW); *S4*, 60% peat moss – pumice (1:1) + 40% compost (3S:1GW); *S5*, 1S:3GW compost; *S6*, 1S:1GW compost; *S7*, 3S:1GW compost; *TOC*, total organic carbon; *TN*, total nitrogen; *CEC*, cation exchange capacity properties in line with Italian and EU regulations and the *Posidonia*-based compost was suitable as a component in growing media (Peruzzi et al. 2020). In particular, the substrate composed of compost (20% of *P. oceanica* and 80% green residues) and decontaminated sediments resulted as suitable for *Viburnum tinus* cultivation. In fact, *V. tinus* had morphological (stem radial growth, dry weight, leaf mass area) and eco-physiological (chlorophyll content, leaf gas exchange, photosynthetic efficiency, and antioxidant activities) responses comparable to those of plants grown on peat (Peruzzi et al. 2021).

The composting strategy has recently been applied in another still ongoing European project, AGRISED. In this project, brackish sediments (S) were co-composted with pruning residues as green waste (GW) in the Czech Republic (CZ) and Italy (IT), as follows (*w*:*w*): 3S:1GW, 1S:1GW, and 1S:3GW. The aim was to demonstrate the suitability of co-composting process for dredged sediments and green waste as well as for the production of suitable growing media for plant nurseries. After 8 and 6 months in the Czech Republic and Italy, respectively, compost stability and maturity were reached and measured with

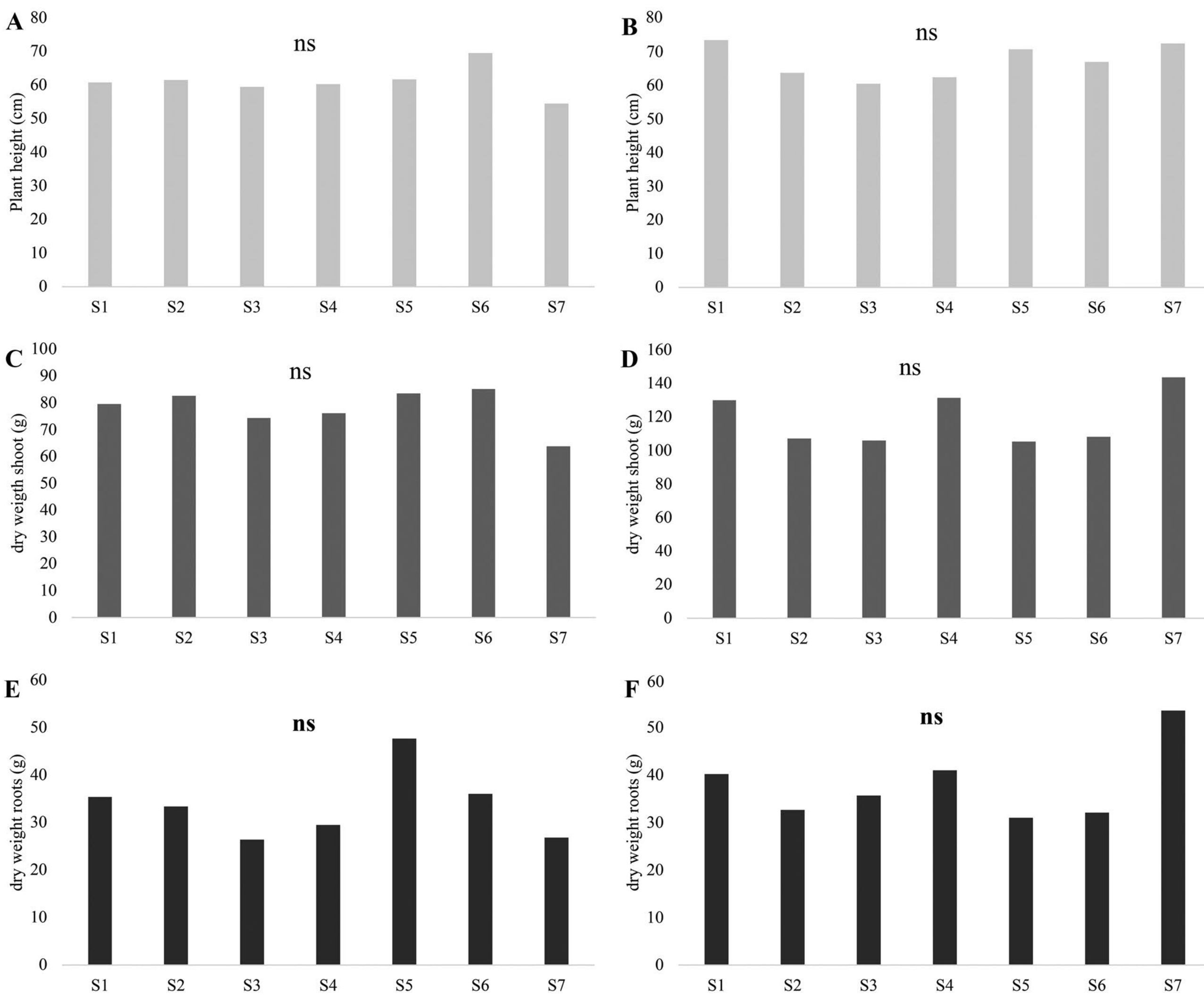

Fig. 1 Plant growth parameters detected in *Photinia x fraseri* (**A**, **C**, **E**) and *Viburnum tinus* (**B**, **D**, **F**) after 5 months of growing on substrates composed of Czech composts. S1 = peat moss – pumice (1:1) as control; S2 = 60% peat moss – pumice (1:1) + 40% compost (1S:3GW); S3 = 60% Peat moss – pumice (1:1) + 40% compost (1S:1GW); S4 = 60% peat moss – pumice (1:1) + 40% compost (3S:1GW); S5 = 1S:3GW compost; S6 = 1S:1GW compost; S7 = 3S:1GW compost; ns = not significant

a decrease and stabilization of organic matter content, electrical conductivity, microbial activity, and the increase of the humification rate (Guo et al. 2019; Gavilanes-Terán et al. 2016; Jurado et al. 2014). At the end of the process, the TOC resulted higher than the law limits in 1S:1GW and 1S:3GW for IT legislation (D. Lgs.75/2010), while no TOC thresholds are reported for CZ legislation (Decree No. 257/2009) (Table 4). However, the TOC/TN ratio under 20 suggested a reached stability for all the CZ and IT co-composts (Gavilanes-Terán et al. 2016). The enzymatic activities confirmed the stability of co-composts (Wittmann et al. 2004); in fact, the total microbial activity significantly decreased over time, specifically −56% in 3S:1GW; −59% in 1S:1GW; −44% in 1S:3GW and 1S:3GW for CZ and −14% in 3S:1GW; −39% in 1S:1GW; −40% in 1S:3GW for IT. The reduced microbial activities were related to the reduction of organic matter readily available during the process, limiting the microbial actions in the maturation phase (Jurado et al. 2014). The maturity of the co-composts is highlighted by EC, showing values below 4.0 dS/m in all co-composts, that indicates the absence of harmful salt content (Chhabra 2004). In addition, the germination index overcame the limit value of 60%, thus demonstrating the lack of toxic elements (Cesaro et al. 2015) and the maturity of all the co-composts. The CZ composts were completely in line with the local legislation regarding sediment reuse in agriculture (Decree No. 257/2009) and the IT composts were generally within the Italian thresholds for growth substrates (D. Lgs. 75/2010), except for conductivity and total organic carbon for 3S:1GW and 1S:1GW (Table 4). The safety was confirmed by the absence of *Salmonella* and the content of *Escherichia coli* (<1000 CFU/g), in line with Italian legislation (D. Lgs. 75/2010). These results showed the effectiveness of the composting process in transforming dredged sediments and green waste into a suitable substrate for plant nurseries. The CZ compost is at the moment in use as a component for growing media for *V. tinus* and *Photinia x fraseri* cultivations, compared to the co-compost-based substrates with the traditional media (S1), made up of peat moss and pumice. Generally, the compost-based substrates revealed physical and chemical properties suitable for plant growth, for Italian legislation (D. Lgs.75/2010), except for TOC that resulted lower than the law limits in S4, due to the low TOC content in 3S:1GW compost (Table 5). The presence of peat in the substrates reduced the EC of the co-composts (S5, S6, S7) as well as the BD, especially in substrates composed of 60% peat and 40% 1S:3GW (S2), reaching the same values of the control (S1). The suitability of the tested substrates was confirmed by the plant growth experiment. In fact, *Photinia x fraseri* and *V. tinus* did not show statistical differences in terms of plant heights and dry matter parameters after 5 months of plant growth (Fig. 1).

4 Conclusions

The CNR-IRET projects contributed to improving brackish and saline sediment management and their recycling strategies. Phytoremediation and landfarming were eco-sustainable technologies that were effective in the remediation of saline and brackish sediments. In fact, the phytoremediation technique reduced the inorganic and organic contamination as well as improving chemical nutritional properties and microbial activities. In addition, the sequential application of landfarming, after phytoremediation, enabled the stimulation of microbial metabolism and the further reduction of organic pollutant concentrations, thus improving sediment characteristics and broadening the possible reuse of sediments to different sectors. In particular, the brackish and saline sediments treated were suitable as a safe component for a wide range of food and non-food crops, contributing to reduce the use of non-renewable materials such as peat. Co-composting was another effective strategy for sediment management that enabled the recovery of sediment with other green wastes (*Posidonia* and green residues). In fact, the maturity and stability of final co-composts were shown by the decrease and stabilization of organic matter content, electrical conductivity, microbial activity, and the increase of humification rate. Generally, the final co-composts and composted based substrates were in line with local legislation, although the addition of organic carbon source to the co-composts was needed. The suitability of compost-based substrates in ornamental plant cultivation was confirmed by the good morphological and physiological responses of the plants, in comparison to the traditional growing media. These results confer a high-quality value to brackish and saline sediments, turning them into a useful and safe material within a circular economy process.

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Declarations

Competing interests The authors declare no competing interests.

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