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Posidonia-Based Compost and Dredged Sediment in Growing Media Improve Tolerance and Nutrient Uptake in Ornamental Plants

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Abstract: Because of the high costs and environmental impacts of peat and chemical fertilizers, the search for sustainable alternatives is increasing. *Posidonia*-based compost (C) has been widely tested as a growing media, while the combination with decontaminated dredged sediments (S) has only recently been studied. Moreover, little information is available on the relationship between plants and growing media. In this work, the suitability of growing media (CS) composed of 100% C, 70% C + 30% S and 30% C + 70% S were investigated compared to peat, for ornamental plants (*Elaeagnus macrophylla*, *Photinia* × *fraseri* and *Viburnum tinus*). Plant growth, physiological, nutritional and antioxidant responses were also investigated. The CS were compliant with current legislation on growing media. The Cu (+60%; +70%), Mg (+11%; +23%) and Ca (+66%; +72%) concentrations were higher in CS with 30% and 70% of S, respectively, than peat. The plants growing in CS had lower antioxidant activities than those on peat, suggesting a better plant tolerance to abiotic stress. In conclusion, the use of CS growing media, especially those with 30% and 70% of S, can be a valuable strategy to replace peat and reduce the application of fertilizers.

Keywords: antioxidant activity; cation ratio; circular economy; dredged sediment; horticulture; nursery plants; peat-free substrate; plant nutrition; *Posidonia oceanica*; soilless cultivation

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1. Introduction

Nowadays, the search for alternative substrates to peat as a growing medium for ornamental plants is increasingly necessary. Due to its excellent chemical and physical characteristics, peat is the most suitable substrate in horticulture. However, with its growing cost, the enormous environmental impact peat causes, and the fact that peat is a non-renewable material, the search for cheap and high-quality alternatives is "mandatory" [1].

In recent years, peat has often been replaced by composts produced from several kinds of organic wastes. This is a trend also driven by the need to recycle waste in an ecological way [2]. *Posidonia oceanica* residues on beaches represent a significant environmental, social, and economic problem due to the high costs of their removal and disposal. *Posidonia* residue has been used in various ways and for many years (for 100,000 years) [3], and *Posidonia oceanica*-based compost has also recently been proposed as a promising growth substrate [4,5]. In particular, Peruzzi et al. [6] have evaluated the possibility of composting *Posidonia oceanica* residues with other wastes, i.e., green waste and remediated dredging sediments for growing media preparation. In previous experiments, tested *Posidonia oceanica*-based compost (C) had given good results regarding stabilisation and maturation. However, only the compost with 20% *Posidonia oceanica* and 80% green waste fully respected the Italian legislation regarding parameters and composition. Subsequently, thanks to the suitability of decontaminated sediments in the composting process with *Posidonia oceanica* residues [6] and by using a global circular economy approach, decontaminated sediments were included as a component of growing substrate in this experimentation. The C was selected at the proportion of 20% as it is the maximum percentage allowed in growing media in Italian regulations.

In fact, sediments dredged from rivers and harbours represent another critical environmental problem. Every year in Europe, an enormous amount, about 100–200 million m^3 [7] is dredged and needs to be disposed of in specific and expensive ways. However, dredged sediments (S) can be recycled as growing substrate after a bioremediation process with extremely promising results [8–13]. Nevertheless, the use of uncontaminated and remediated S in agriculture is permitted only in some European countries [14,15], while it is not allowed in the EU regulations in fertilizers [16], and in Italian legislation [17]. This fact is probably due to a lack of knowledge of the beneficial agronomic properties and human and environmental safety of dredged decontaminated sediments. Making the application of S more widespread in agriculture could help raise policymakers' awareness of the economic and environmental benefits that the use of sediments in agriculture would bring, in the hope of a rapid revision of fertilizer regulations.

The association of C with bioremediated S in a growth substrate (CS) would allow to solve the management problem of two widely produced wastes as well as to overcoming some limitations that the sediments have as an agronomic substrate, namely the very high bulk density and the low content in organic carbon and total nitrogen. In addition, the contribution of micro and macro nutrients by sediments [18] could limit the need for plant fertilization.

However, little information is available on the plant and growing media relationship. In fact, a few studies have focused on the use of S with C as growing media for ornamental plants.

The aims of this study were to assess the suitability of CS for ornamental plant cultivation, starting from the experiment carried out by [19] and investigating the relationship between the chemical properties of growing media and the plant responses in terms of nutrition and antioxidant activities.

2. Materials and Methods

2.1. Experimental Design

Posidonia oceanica-based composting (C) was carried out for six months with 20% *P. oceanica* and 80% green wastes, as reported by [6]. Sediments (S) dredged from Leghorn port (Tuscany Region, Italy) were remediated for about two years through phytoremediation and for three months treated with landfarming within the framework of the following European projects: AGRIPORT (ECO/08/239065/S12.532262), LIFE CLEANSED (LIFE12 ENV/IT/000652) and LIFE HORTISED (LIFE14 ENV/IT/000113). The details regarding sediment decontamination and recycling were reported in [11–13,20]. The primary chemical characteristics of sediment used are reported in Table 1.

In May 2018, the plant trials were set up in the Pistoia nursery district (Tuscany Region, Italy). Thirty-six pots of 30 litres each (37 cm Ø and 33.5 cm h) were filled with four different growing media (28 litres of growing media in each pot): 100% *Posidonia*-based compost (100 CS); 70% *Posidonia*-based compost and 30% decontaminated sediments (70 CS); 30% *Posidonia*-based compost and 70% decontaminated sediments (30 CS) and 100% Peat (P) as a control.

Three (2-year-old) ornamental plant species, commonly cultivated in the Pistoia (Italy) nursery sector, were selected: *Photinia* × *fraseri*, a fast-growing plant, sensitive to the properties of the growing media [21], *Viburnum tinus* L., a xerophytic and slow-growing species, less sensitive to substrate chemical properties [22], and *Elaeagnus macrophylla* L. for its tolerance to poor soil conditions [23].

Three replicates were made for each substrate-plant combination. The pots (36 pots: 3 plants × 4 treatments × 3 replicates) were kept for six months under open field conditions, and the substrate was irrigated to maintain the field capacity. Traditional practices of pest control, but no fertilization, were applied. The different substrates were sampled in May 2018 (the start of the first vegetative cycle) and October 2018 (at the end of the first vegetative cycle). Five samples were taken using a soil core sampler (1.5 cm diameter, 30 cm length) from each pot and combined to obtain a composite sample. Soil samples were air-dried, sieved (2 mm) and stored at room temperature until analysis. At the end of the growing cycle, samplings and surveys on the vegetation were also carried out (Figure 1).

Table 1. Chemical and physical properties of *Posidonia*- and sediment-based growing media and their components in comparison to national and international legislated values.

Indicator	Italian Regulation 75/2010 [1]		EU Fertilisers Regulation [2]					
	Base Growing Media	Mixed Growing Media	Growing Medium	S **	P **	100 CS **	30 CS	70 CS **
Zn (mg kg^{-1})	<500 *		<500	237	15.2	35.2	182	115
Cd (mg kg^{-1})	<1.5 *		<1.5	<0.5	<0.5	<0.5	<0.5	<0.5
Ni (mg kg^{-1})	<100 *		<50	44.3	9.65	28.6	35.3	29.1
Pb (mg kg^{-1})	<140 *		<120	46.1	15.8	12.8	39.1	35.8
Cu (mg kg^{-1})	<230 *		<200	51.7	12.5	12.3	41.2	30.1
Hg (mg kg^{-1})	<1.5 *		<1	<0.2	<0.2	<0.2	<0.2	<0.2
Total organic carbon(%)	>8	>4		1.81	27.9	22.2	7.65	3.33
Total Nitrogen (%)					1.031	0.579	0.334	0.158
pH	3.5–7.5	4.5–8.5		8.6	6.7	6.7	7.6	7.4
Electrical conductivity (dS m^{-1})	<0.7	<1		0.28	0.30	0.70	0.19	0.19
Dry Bulk density (g cm^{-3})	<0.45	<0.95		1.36	0.36	0.29	0.66	0.86

S = decontaminated sediment; P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments. [1] Reorganization and review of the fertilizer regulations (Riordino e revisione della disciplina in materia di fertilizzanti) Decreto legislativo 75/2010. [2] REGULATION (EU) 2019/1009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003; * Reference value for compost material. ** data from Peruzzi et al. [19].

2.2. Growing Media Characterisation

Each growing media's chemical and physical properties were analysed at the beginning and end of the vegetative cycle. The pH and electrical conductivity (EC) were estimated on water extract (1:5, *v/v*) [24,25]. Total organic carbon (TOC) and total nitrogen (TN) were assessed by RC-412 multiphase carbon and FP-528 protein/nitrogen (LECO Corporation, St. Joseph, MI, USA). For the determination of heavy metals and micro- and macro-nutrients, samples were digested with HNO_3 and H_2O_2 before ICP–OES (Agilent, Santa Clara, CA, USA). Dry bulk density (BD) was determined through a water retention curve obtained using the gravitational drainage technique for soil improvers and growing media [26]. The ratios of nutrients (cation ratio) in the growing media (Ca/Mg, K/Mg, Mg/K and (Ca + Mg)/K) were calculated from concentrations [27]. The properties of each tested growing media were compared to the Italian and European law limits.

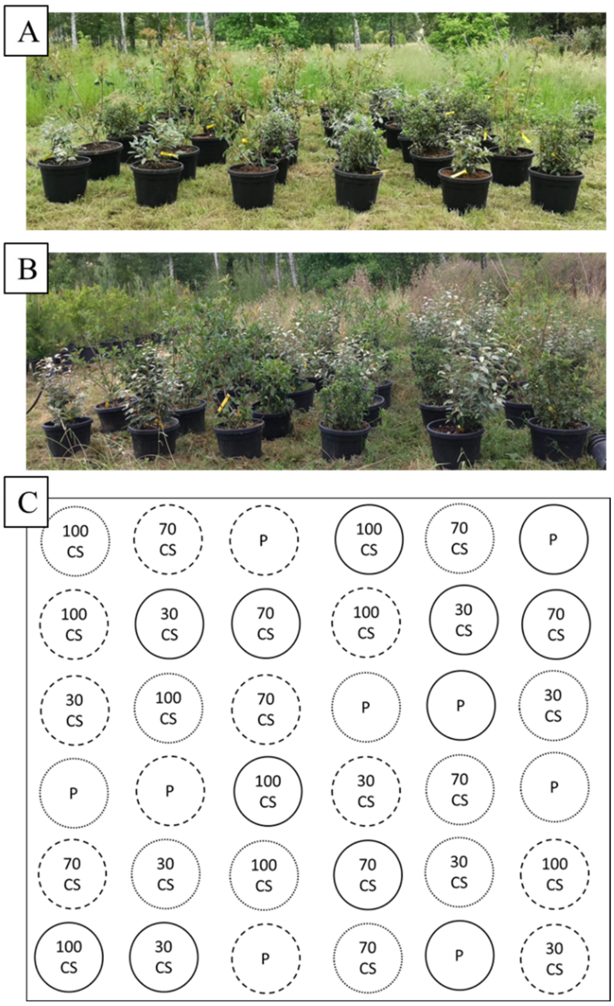

Figure 1. *Elaeagnus macrophylla*, *Photinia* × *fraseri* and *Viburnum tinus* at the beginning (**A**) and after 4 months of growing (August 2018) (**B**) and the experimental design (**C**). Continuous, dashed and dot-line circles represent pots with *Elaeagnus macrophylla*, *Photinia* × *fraseri* and *Viburnum tinus*, respectively. P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments.

2.3. Plant Growth and Physiology

The percentage of stem radial growth (SRG) was calculated for each plant by the ratio between the stem diameter at the end and at the beginning of the vegetative cycle [19], taken at 3 cm from the soil using a digital calliper.

At the end of the cycle, on each plant the stomatal conductance (GS), transpiration rate (TR) and net photosynthesis (PN) were measured on three young, fully expanded leaves using a CIRAS-2 Infrared Gas Analyzer (PPSystem, Amesbury, MA, USA). Chlorophyll a concentration was determined using the acetone extraction and spectrophotometric method [28]. In addition, the plant antioxidant activities were determined according to Souid protocol [29], and the method proposed by Bradford [30] was used for protein determination. Superoxide dismutase (SOD) activity was measured through the inhibition of the photochemical reduction of nitro-blue-tetrazolium (NBT) [31]. Guaiacol peroxidase (GPX) activity was analysed following the H_2O_2-induced guaiacol oxidation by absorbance change (470 nm) [32]. Ascorbate peroxidase (APX) was measured as the ascorbate oxidation by the decrease in absorbance at 290 nm, with an absorbance coefficient of 2.8 mM^{-1} cm^{-1}) [33].

Leaf nutrient concentrations were determined on dried and grounded leaves after a wet digested with HNO_3 and H_2O_2, and the concentrations were determined with ICP–OES (Agilent, Santa Clara, CA, USA).

2.4. Statistical Analysis

Statistical analysis was performed using the STATISTICA 7.0 software (StatSoft Inc., Tulsa, OK, USA). Differences in growing media were evaluated employing the analysis of variance (one-way ANOVA), followed by the HSD Tukey's test ($p < 0.05$). In addition, the principal component analysis (PCA) was performed on the plant and substrate nutrient data and antioxidant activities with a statistical difference to compare the relationship between growing media and plant performance.

3. Results

3.1. Growing Media Properties

The chemical and physical properties of the tested growing media at the beginning of the vegetative cycle are reported in Table 1, in comparison with Italian and European legislated values. The concentrations of heavy metals in all tested growing media showed values lower than the threshold defined by these legislations. The TOC in 70 CS resulted lower than the Italian regulations allowed for mixed and base growing media and in 30 CS for base growing media. The pH, EC and BD showed values in line with those accepted by Italian legislation.

The concentrations of micro- and macro-nutrients were significantly higher in the 70 and 30 CS growing media than in peat (Table 2). In fact, the concentrations of Cu (+60%; +70%), Mg (+11%; +23%) and Ca (+66%; +72%) were higher in 30 CS and 70 CS, respectively, than peat. The Ca/Mg ratio was in the ideal range (2–5) and higher in all CS than in peat, while Mg/K was acceptable in CS as well as in peat. Finally, in all substrates Ca/K and (Ca + Mg)/K resulted suitable for growing media (Table 1). At the end of the vegetative cycle, the ratios depended also on the species growing on the substrates. The Ca/Mg ratio resulted higher than the ideal value of 5 in 100 CS for *P.* × *fraseri* and in peat for *V. tinus*, indicating Mg deficiency, while it was lower than 2 in *P.* × *fraseri* growing on peat, indicating low Ca/Mg. The Mg/K ratio was in an acceptable range (1–3) in all tested substrates except for peat in *V. tinus* and *E. macrophylla*. Ca/K and (Ca + Mg)/K ratios maintained suitable values for K availability (Figure 2).

3.2. Plant Growth and Physiological Responses

Elaeagnus macrophylla, *P.* × *fraseri* and *V. tinus*, grown on all tested growing media, showed no significant differences in SRG. The same results were also observed for GS and TR in the three species. However, the PN showed similar trend in all species, with lower values in CS30 and it specifically resulted significantly higher in *E. macrophylla* grown on 70 CS and in *P.* × *fraseri* and *Viburnum tinus* plants grown on 100 CS (Table 3). On the other hand, the chlorophyll concentration within each species showed no statistical differences between growing media.

Table 2. Total micro-(Zn and Cu) and macro-(K, Mg and Ca) nutrient concentrations (mg kg^{-1} dry weight) and nutritional ratios were detected in growing media at the beginning of the experiment.

	P	100 CS	70 CS	30 CS	Reference Values *	
Zn	15a **	35b **	115c	182d **		
Cu	12a **	12a **	30b	41c **		
K	2500b	2190a	2902c	3414d		
Mg	5000a	4460a	5605b	6471b		
Ca	8000a	17,400b	23,960c	28,544c		
Ca/Mg	1.6a	3.9b	4.2b	4.4b	<1	Calcium deficiency
					1–2	Low level of Ca to Mg
					2–5	ideal
					>5	Mg deficiency
Mg/K	2.0a	2.0a	1.9a	1.9a	<1	Mg deficiency
					1–3	Acceptable
					3	ideal
					3–18	Acceptable
					>18	K deficiency
Ca/K	3.2a	7.9b	8.3b	8.4b	<30	suitable
					>30	K deficiency
(Ca + Mg)/K	5.2a	10.0b	10.2b	10.3b	<40	K suitable
					>40	K deficiency

Different letters represent a statistical difference for $p < 0.05$ within each plant species. P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments; * References values from Rodelo-Torrent et al. (2022); ** Rodelo-Torrent et al. [19].

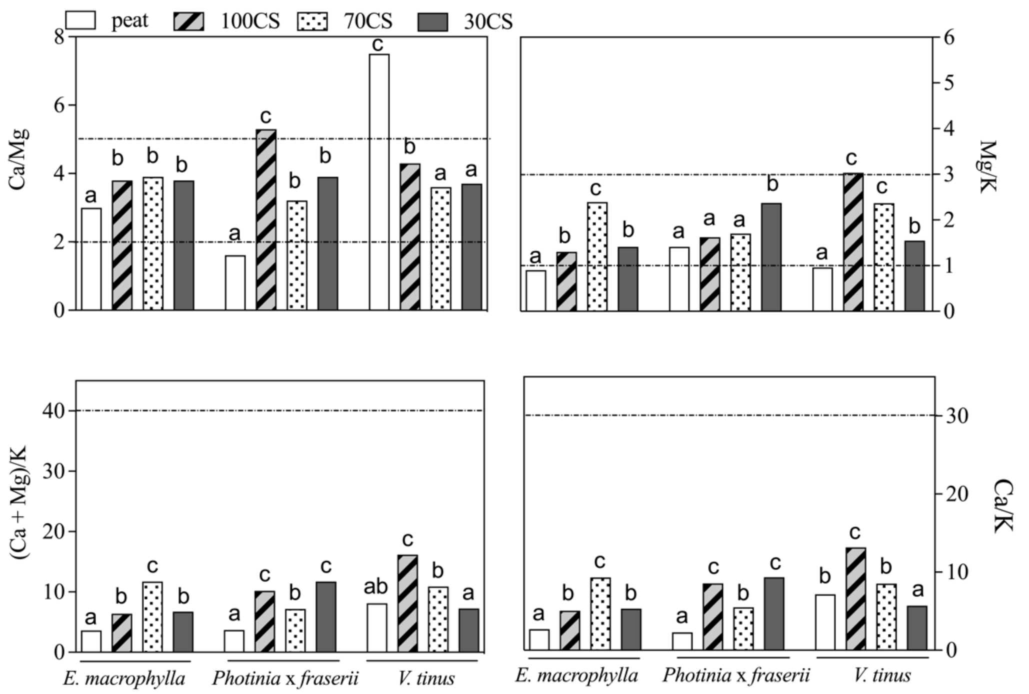

Figure 2. Cation ratios in *Elaeagnus macrophylla*, *Photinia* × *fraseri* and *Viburnum tinus* at the end of the vegetative cycle. P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments. Different letters represent a statistical difference for $p < 0.05$ within each plant species. Dotted lines represent the ideal limits for Rodelo-Torrent et al. [27].

Table 3. Plant growth and physiological responses of *Elaeagnus macrophylla*, *Photinia × fraseri* and *Viburnum tinus* growing on different growing media at the end of the vegetative cycle. Different letters represent a statistical difference for $p < 0.05$.

		E. macrophylla				*Photinia × fraseri*				*V. tinus*			
		P	100 CS	70 CS	30 CS	P	100 CS	70 CS	30 CS	P	100 CS	70 CS	30 CS
SRG	%	261a	256a	253a	204a	215a	179a	180a	170a	170a *	141a	159a *	118a
GS	mmol m^{-2} s^{-1}	115a	126a	190a	117a	72a	126a	85a	82a	110a *	98a	93a *	61a
TR	mmol H_2O m^{-2} s^{-1}	2.44a	2.52a	3.43b	2.44a	1.67a	2.51a	2.08a	1.81a	2.49a *	2.20a	2.07a *	1.53a
PN	µmol CO_2 m^{-2} s^{-1}	8.00a	8.35a	13.73b	7.80a	4.52a	7.60b	5.70a	3.83a	8.10ab *	9.37b	6.70ab *	3.60a
Chl *a*	mg g^{-1} dy weight	967a	1096a	937a	902a	940a	666a	791a	864a	1291a	1198a	1266a	1420a

Different letters represent a statistical difference for $p < 0.05$ within each plant species. P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments; SRG = stem radial growth; GS = stomatal conductance; TR = transpiration rate; PN = net photosynthesis; Chl *a* = chlorophyll a concentration. * Data from Peruzzi et al. [19].

The leaf nutrient concentrations are reported in Table 4. In *E. macrophylla* leaves, Zn had significantly higher values in 100 and 30 CS, in *P. × fraseri* in 30 CS and *V. tinus* in 100, and 70 CS. Significantly higher Cu concentration was detected in *E. macrophylla* and *P. × fraseri* leaves in 30 CS and in *V. tinus* on 100, 70 and 30 CS substrates. The Mn concentration in *Elaeagnus macrophylla* and *Viburnum tinus* was significantly higher in 70 CS and 30 CS, while in *Photinia × fraseri* only in 70 CS. Regarding K, the leaf concentration in *E. macrophylla* was similar in all growing media. In contrast, in *P. × fraseri* and *V. tinus*, K concentration was slightly higher in plants grown in P, followed by those in 100 CS and 70 CS, while the leaf concentration resulted lower in 30 CS compared to peat. The Mg concentration in *E. macrophylla* leaves showed significantly higher values in P, 100 CS and 30 CS, while in *P. × fraseri* the leaves did not show significant differences. In *V. tinus*, the concentration of Mg resulted significantly higher in all CS growing media than in P. The concentration of Ca in *E. macrophylla* was significantly higher in 30 CS, while in *P. × fraseri* and *V. tinus* in all CS substrates as compared to P.

Table 4. Leaf nutrient concentrations in *Elaeagnus macrophylla*, *Photinia × fraseri* and *Viburnum tinus* growing on different growing media at the end of the vegetative cycle.

		E. macrophylla				*Photinia × fraseri*				*V. tinus*			
		P	100 CS	70 CS	30 CS	P	100 CS	70 CS	30 CS	P	100 CS	70 CS	30 CS
Zn	mg kg^{-1}	3.91a	8.59b	4.02a	9.02b	2.64a	3.85a	1.88a	6.38b	4.90a	10.7c	10.4bc	8.92b
Cu	mg kg^{-1}	3.11a	3.74a	6.95b	9.86c	2.10a	2.41ab	1.87a	2.66b	4.67a	5.28b	5.63b	6.64b
Mn	mg kg^{-1}	173b	127a	203bc	218c	46a	45a	67b	46a	102a	117a	148b	180c
K	g kg^{-1}	5.98a	5.36a	4.54a	4.87a	8.92b	7.87ab	7.82ab	6.78a	9.23b	7.43a	8.14ab	6.67a
Mg	g kg^{-1}	1.01b	1.03b	0.86a	1.07b	1.87a	2.12a	1.72a	1.92a	1.39a	1.76b	1.49ab	1.88b
Ca	g kg^{-1}	5.64a	6.32a	6.39a	8.08b	7.57a	11.9b	8.25b	11.9b	2.91a	5.22b	4.43ab	6.17b

Different letters represent a statistical difference for $p < 0.05$ within each plant species. P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments.

The SOD, GPX and APX activities showed significantly lower activities in *E. macrophylla* and *P. × fraseri* for all tested growing media compared to peat (Figure 3). This reduction was also detected for *V. tinus*, except for plants grown on 30 CS, which showed similar values for SOD compared to peat. In addition, among the CS growing media, in all species SOD, GPX and APX activities were higher in 30 CS.

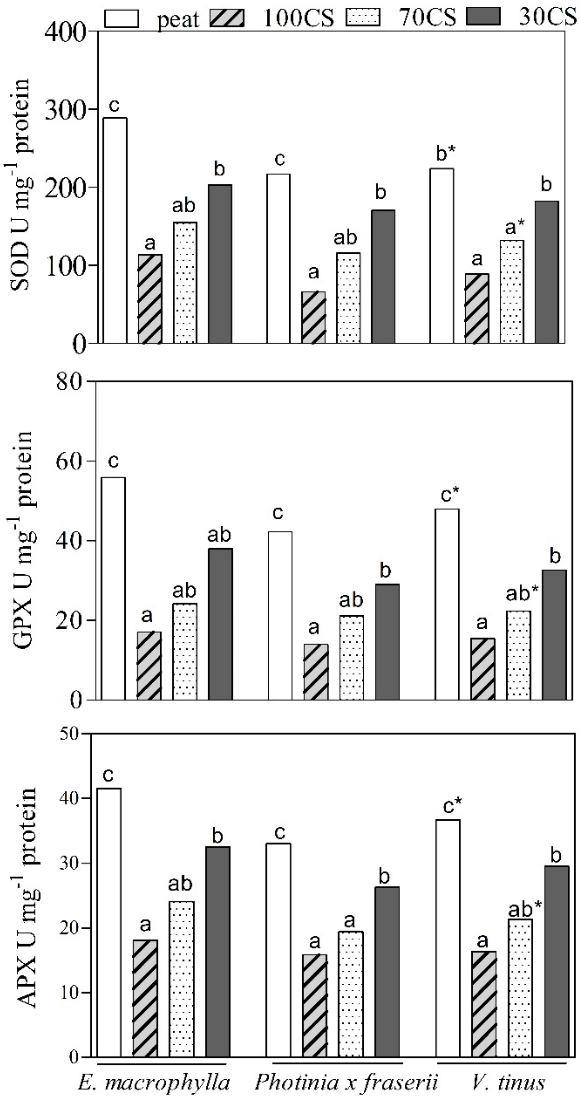

Figure 3. Superoxide dismutase (SOD), guaiacol peroxidase (GPX), and ascorbate peroxidase (APX) activities were detected in *Elaeagnus macrophylla, Photinia* × *fraseri* and *Viburnum tinus* at the end of the vegetative cycle. Different letters represent a statistical difference for $p < 0.05$. P = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments. * Data from Peruzzi et al. [19].

3.3. Plant-Growing Media Relationship

A total of 65% of the total variance is explained by two PCs (Table 5, Figure 4). The shift from the left to the right side of Figure 3, along with the PC1 values, showed the different plant responses related to plant nutrition. For example, *E. Macrophylla* and *P.* × *fraseri* showed opposite behaviour as regards micro- and macro-nutrient accumulations in leaves. The shift from the bottom to the top towards positive values of PC2 reflected the effect of growing media properties on plant performance. In particular, the plants grown on peat were more stressed than the ones grown on CS growing media, as highlighted by the higher antioxidant activities.

Table 5. Principal component loadings. SOD = superoxide dismutase; GPX = guaiacol peroxidase; APX = Ascorbate peroxidase. The element data refers to leaf concentrations. * = parameters used for PCA interpretation.

	PC1	PC2
SOD	−0.917 *	0.009
GPX	−0.898 *	0.079
APX	−0.869 *	0.018
Cu l	−0.109	−0.896 *
Zn l	0.243	−0.629 *
Mn l	−0.529	−0.786 *
K l	0.112	0.626 *
Mg l	0.452	0.661 *
Ca l	0.387	0.430
PN	0.051	−0.546
Mg/K	0.771 *	−0.311
Ca/K	0.770 *	−0.328
(Ca + Mg)/K	0.815 *	−0.343
Proportion of variance	38.28%	26.60%
Cumulative proportion of variance	38.28%	64.88%

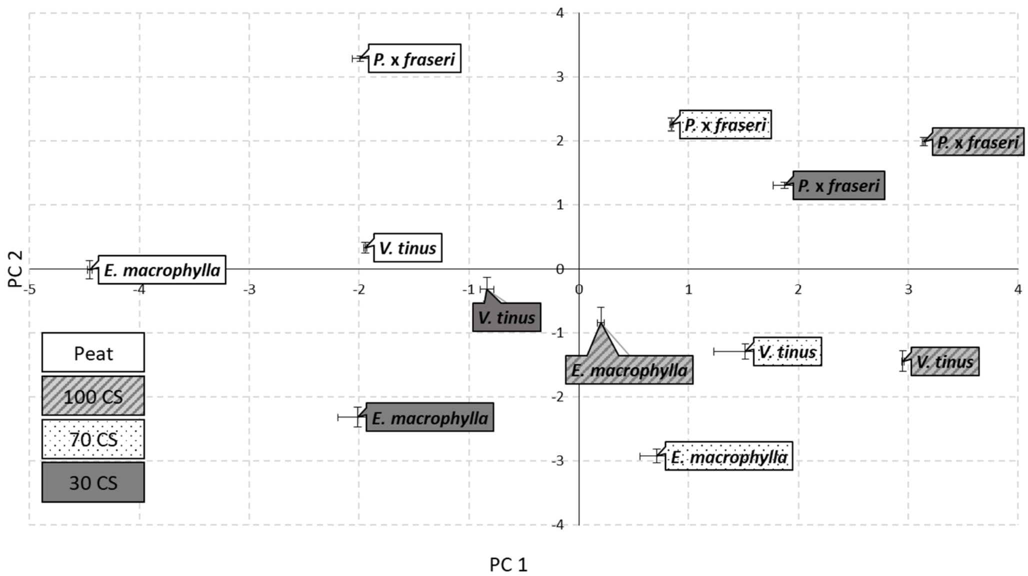

Figure 4. Principal component analysis on growing media properties (cation ratio) and plant data (antioxidant activities and leaf nutrient concentration) of *Elaeagnus macrophylla*, *Photinia* × *fraseri* and *Viburnum tinus* at the end of the vegetative cycle. Peat = 100% Peat; 100 CS = 100% *Posidonia*-based compost; 70 CS = 70% *Posidonia*-based compost and 30% decontaminated sediments; 30 CS = 30% *Posidonia*-based compost and 70% decontaminated sediments.

4. Discussion

The use of reclaimed sediment has been demonstrated to be suitable for ornamental plant cultivation and contributes to the reduction in non-renewable raw materials exploitation, such as peat [8,9]. In particular, the addition of sediment has been found to improve the nutritional component of the substrate [18]. Obviously, such new substrates must be authorized to be further used outside of an experimental trial. Therefore, the chemical and the physical properties of the substrate made from these materials must be compared to the legal thresholds and the characteristics standardized to promote the integration of decontaminated sediments in the list of permitted fertilizers in the EU legislation. *Posidonia*-based compost has also demonstrated its suitability for the agricultural sector [5,19,34,35].

In this trial, all the tested growing media (100 CS, 70 CS and 30 CS) revealed chemical and physical properties in line with the international and national laws, as also found by Peruzi et al. [19]. The higher the percentage of sediments the higher the nutrient concentration in the growing media, as also seen by Ugolini et al. [8] in substrates with sediment and soil. Adding 30% and 70% of decontaminated sediment to *Posidonia*-based compost enriched the CS growing media of micro-(Zn, Cu) and macro-(Mg, Ca) nutrients. In these substrates, the concentration was even higher than in the *Posidonia*-based compost [4,35] and peat, mainly due to the chemical characteristics of the original materials. For example, at the beginning of the experiment, Ca was more than three- and twofold higher in 30 CS, 70 CS and 100 CS, respectively, than in peat. The Zn content in the substrates 30 CS and 70 CS was respectively twelve- and eightfold higher than in peat, while the contribution was less marked in 100 CS (twofold). In 30 CS and 70 CS, Cu also was, respectively, more than three- and twofold higher than in peat, while in 100 CS it was similar to that in peat. The high content of Ca, Zn and Cu in the substrates with sediments is linked to this type of matrix, which is naturally rich in calcium carbonate depositions and shells and in the other elements, as found in previous studies [8,18]. The Mg and K showed the same pattern with only slightly higher values in 30 CS and 70 CS (about 1.3 and 1.1 times greater, respectively) than in peat and lower values in 100 CS (0.9 times). This fact confirmed the importance of dredged sediment as a source of macro- and micronutrients, which are beneficial for plant growth [18]. Therefore, the improved nutrient concentrations in the growing media can reduce the possible use of chemical fertilizers, essential for plant cultivation on peat-based substrates, which are usually poor in nutrient content [36] so requiring reintegration. This fact was also evident in the cation ratios. The CS growing media showed nutrient ratios for Ca, Mg and K in an ideal range for plant growth. The Ca/Mg ratio improved in the CS-growing media with respect to peat.

However, the substrate-plant relationship also showed some inconsistencies. At the end of the experiment, the lowest leaf concentration of Ca in the three species was found when they grew in peat. A trend with higher values in 30 CS, followed by 70 CS, was found especially in *E. macrophylla* and *V. tinus*, whilst no relevant differences between the peat-alternative substrates were found for *P.* × *fraseri*. Therefore, Ca absorption only partially depended upon the initial concentrations of the element in the substrates, and we may assume that *P.* × *fraseri*, which showed the highest values, would be the most effective in element absorption. Furthermore, the Ca/Mg ratio showed some slight differences between substrates by species. Notably, in the pots with *V. tinus* the Ca/Mg ratio increased especially in peat, then in 70 CS and 30 CS, indicating a likely Mg deficiency due to decrease in absorption when peat is present. In the case of *P.* × *fraseri*, the ratio clearly increased in 100 CS while it decreased in peat, indicating a Mg deficiency in 100 CSn and a Ca deficiency in peat. Due to their chemical similarity, high Ca levels (as found especially in substrates with sediments) can reduce the availability of Mg, while the amount of organic matter and clay, which determines the cation exchange capacity, increases the elements' availability [27]. The presence of sediments in combination with the *Posidonia*-based compost guaranteed an optimal range of Ca and Mg for *P.* × *fraseri* growth. In contrast, *E. macrophylla* substrates, at the end of the vegetative cycle, did not show any Mg or Ca deficiency. This fact is probably due to the arbuscular mycorrhizal characterizing the roots of *E. macrophylla*, which facilitate an optimal element absorption [37]. At the end of the vegetative season, the leaf content of Mg was similar in most treatments, with a trend of slightly higher values in substrates rich in sediments (30 CS) and organic matter (100 CS and P) than in 70 CS especially in *E. macrophylla* and *P.* × *fraseri*. The increase in leaf nutrient concentrations in plants growing on decontaminated sediment has also been observed by Tozzi et al. [11], in lettuce, especially for Ca, Mg and Fe. The Mg/K ratio < 1 in peat with *V. tinus* and *E. macrophylla* confirmed the Mg deficiency in this substrate.

Despite, in 30 CS, K showing the highest concentration at the beginning of the experiment, the leaf concentration in the plants growing on this substrate (especially in *P.* × *fraseri* and in *V. tinus*) was the lowest. This can be explained by the fact that K binds with clay minerals structure, thus becoming unavailable for plants [38]. The lower K content in the leaves could likely have affected, although not significantly, the stomatal conductance and photosynthesis of these species, confirming the critical role of K in the gas exchange regulation [39].

The leaf concentration of Cu in *E. macrophylla* clearly followed the trend of the substrate: the higher the sediment concentration in the substrate, the higher the leaf content. Additionally, in *V. tinus* the highest leaf concentrations of Cu and Zn were found when growing in CS growing media. This implies the role of the organic matter (*Posidonia*-based compost) in the availability of the nutrients as found for Cu in combination with the rhizosphere, which may decrease the bond with organic matter [40] and for Zn [41].

The excellent health status of the tested ornamental plants on CS growing media was also confirmed by their growth rate and eco-physiological response. Similar results were reported by Ugolini et al. [8] for these ornamental plants grown on substrates composed of phyto-remediated sediments and soil, suggesting the plants' adaptability to different peat-free substrates composed of sediment. In particular, the 70 and 100 CS growing media positively influenced the net photosynthesis in *Elaeagnus macrophylla* and *Photinia* × *fraseri*. This suggests an optimal growth condition on CS growing media, compared to peat, as the photosynthesis is highly sensitive to abiotic stress [42]. An enhanced photosynthetic performance is also positive to limit photoinhibition risks [43], especially those related to transplanting stress, such as waterlogging or drought [44].

The improved nutritional status of the CS growing media contributed to the high leaf nutrient concentrations, which results in an optimal growth [45]. The Mg leaf concentrations have been demonstrated to be similar in all CS growing media, indicating good maintenance of photosynthesis performance [46]. In addition, plants did not show changes in chlorophyll content, as chlorophyll degradation should be expected at Mg-limited conditions [47].

The addition of 70% of decontaminated sediment enhanced the concentrations of Ca and Cu in *Elaeagnus macrophylla* and *Viburnum tinus* with values in line with the optimal values of 5000 and 6 mg kg^{-1}, respectively [44]. The increase in leaf nutrient concentrations in plants growing on decontaminated sediment has also been observed by Tozzi et al. [11], in lettuce, especially for Ca, Mg and Fe.

In our research, the reduction in antioxidant activities highlighted the excellent performance of the tested ornamental plants on CS growing media. The SOD, APX and GPX activities, as primary defence mechanisms against abiotic stress, were reduced in plants grown on CS substrates, especially in 100 and 70 CS, confirming less exposure to unfavourable conditions [20,47], while they were higher in plants growing on peat, indicating a nutrient deficiency in this substrate. A similar response was observed in a hydroponic experiment in *Zea mays* L., where the increase in the antioxidative enzyme activities was due to macronutrient deficiency [48]. In addition, the PCA indicated that the antioxidant activities are negatively correlated to the cation ratios, confirming the CS growing media's role in improving plant tolerance to stress. The PCA also revealed different responses for *P.* × *fraserii* and *E. macrophylla* in the accumulation of macro- and micro-nutrients in leaves amongst the ornamental plants. This could be related to the species' varying characteristics, specifically the ability of *E. macrophylla* to grow on poor and degraded soil [23] with respect to the greater nutrient requirement of *P.* × *fraseri.*

5. Conclusions

Growing media made of *Posidonia*-based compost and decontaminated sediment complied with EU and the Italian fertilizer regulations, especially when the *Posidonia*-based compost was limited to 30%. Dredged and decontaminated marine sediments improved the nutrients' concentration in growing media at lower (30%) and higher (70%) concentrations, thus becoming a long-term source of micro- and macro-nutrients for evergreen plants as compared to peat. Furthermore, the sediment application and the enhanced nutrient status in the growing media reduced the plant antioxidant activity observed on peat. Growing media, composed of *Posidonia*-based compost and sediment resulted a sustainable strategy for a complete peat replacement, reducing the need for chemical fertilizer application. More investigations are needed to understand the long-term availability of micro- and macro-nutrients in such mixtures to the plants and in which concentrations they can be used to optimize the use of components, depending on their availability.

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