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Co-Composting of Green Waste and Dredged Sediments Can Reduce the Environmental Impact of the Potted Nursery without Affecting Plant Growth

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Abstract: The ornamental nursery industry is steadily growing in Europe, and a consequent increase in the demand for substrates related to container plant cultivations is expected in the coming years. Currently, substrates consist in part or entirely of peat, a non-renewable resource with concerns about its environmental impact due to extraction, transport, and use. Therefore, it is essential to focus on alternative materials, particularly waste by-products to be recycled as components of substrates to achieve more sustainable cultivations. In this study, substrates obtained by mixing co-composted dredged sediments (S) and green waste (GW) in different ratios (1:3; 1:1; 3:1) were tested for cultivation, and plant growth was compared with a control growing media (peat and pumice in a 1:1 ratio). The cultivation trial lasted for one year and was carried out on two potted ornamental evergreen shrubs (*Photinia* × *fraseri* and *Viburnum tinus*). The results showed that the plant growth parameters of both species, occurring in substrates with co-composted materials, were not significantly affected compared to the control, with the exception of below-ground biomass in *V. tinus*. Moreover, a Life Cycle Assessment (LCA) analysis was carried out to quantify the greenhouse gas emissions (GHG) deriving from the replacement of peat with the other proposed substrates. The functional unit was 10 L (Ø 24 cm) potted plants and the results were expressed in kg of CO_2 equivalent (kg CO_2eq). We demonstrated that the replacement of peat-based substrates with the alternative substrates was able to reduce the GHG emission by an average of 11.56 to 23.13%. Higher GHG emissions were related to the cultivation phase (0.9 kg CO_2eq/plant), and while comparing substrates, we obtained an average percentage reduction of 28.1% to 59.6%. Thus, our results suggest that co-composted mixtures of dredged sediments with green waste could be used as sustainable techno-soils for pot nursery cultivation of ornamental species with reduced environmental impact.

Keywords: by-product; carbon footprint; greenhouse gas emissions; growing media; ornamental nursery; substrates

1. Introduction

The ornamental plant sector has globally undergone a significant increase in recent years, both in terms of production and demand, and its further development is expected, especially in Europe, over the next decade [1]. Similarly, the production of hardy ornamental nursery stocks has steadily increased over the last 40–50 years [2,3], and it is now considered of great importance throughout Europe, reaching an economic value of approximately EUR 20 billion per year since 2010 [4]. In particular, the Netherlands leads the European table with more than 5 billion EUR/year derived from the production of plants and flowers, followed by Italy, Germany, France, and Spain. In Italy, Pistoia (43°54′ N, 10°41′ E. 30 a.s.l.), near Florence, is considered the greatest plant nursery district, playing a prominent role with about 1000 ha of container-grown plants [5]. Currently, most of the substrates used in potted plant production are peat-based [6–9], but environmental concerns about peatlands [10] due to intense peat mining [11,12] have led researchers and stakeholders to explore alternative and more eco-friendly materials as potting mixes [13–15]. In recent years, raw or composted waste by-products, such as mushroom compost [2], paper mill sludge [2,16], almond shell waste [17], and coir (or coconut fiber) [18,19] were tested as a total or partial alternative to peat moss in the growing media, with variable results in terms of growth and quality of plant production. Amongst them, one of the most interesting waste by-products is represented by dredged marine and river sediments [20–24]. Although the micro- and macro-nutrient contents of dredged sediments make these matrices a good candidate as peat-free growing media, the presence of high levels of hydrocarbons and heavy metals limits their recycling in agriculture [22]. The application of low-cost biological technologies (e.g., co-composting) can reduce the organic as well as the inorganic contamination and improve the physical, chemical, and biological properties of dredged sediments, making a suitable substrate for plant growth [25,26]. However, the remediated sediments are not currently included in the European and Italian regulations as fertilizers or agronomic substrates [27], although the efficiency of dredged sediment recovery and recycling has been widely demonstrated.

Moreover, the evaluation of the effect of peat's partial or total replacement with a waste material in terms of CO_2 emissions and other environmental concerns became a relevant goal. Life Cycle Assessment (LCA) is a technique widely used to evaluate the environmental impact of a production system or product itself [28], and it is considered a helpful methodology for defining and quantifying greenhouse gas (GHG) emissions and other environmental impacts [5,29]. LCA has already been used in several agricultural systems, considering either the entire life cycle ("cradle to grave" approach) or only a stage of the process (e.g., "gate to gate") [30–34].

Therefore, the research hypothesis was to verify whether peat could be replaced by waste products in the pot nursery industry without compromising plant growth and increasing CO_2 savings.

The present study expands and completes our preliminary research [35] about the suitability of dredged river sediments (S) composted with agricultural green waste (GW) as a replacement growing media for ornamental plants as part of the Life project AGRISED (LIFE17 ENV/IT/269). Different ratios of S and GW were tested to remediate sediment contamination and optimize their management, following Italian and European legislation. Once the co-composting phase was completed, a one-year cultivation phase was performed to evaluate the effect of sediments assembled with these waste by-products on the growth of two ornamental container-grown shrubs (i.e., *Photinia* × *fraseri* Dress. and *Viburnum tinus* L.). At the same time, all various steps of the production chain were subjected to environmental analysis using LCA methodology. Thus, the main objectives of the current study are (i) to explore the performances of co-composted mixtures of S and GW as innovative techno-soils for the nursery cultivation of ornamental species; and (ii) to calculate the environmental impact, in terms of GHG emissions, derived from the replacement of peat with these waste matrices through an LCA analysis in container plant nurseries.

2. Materials and Methods

To better follow the research, a list of acronyms for all summarized terms and their explanation is provided in Table 1. Moreover, a flowchart for summarizing this section is provided in Figure S1.

Table 1. List of acronyms used in this study and relevant explanation.

Acronyms	Explanation
AC	Air Capacity
BD	Bulk Density
CGM	Control Growing Media
EAW	Easily Available Water
EC	Electrical Conductivity
GHG	Greenhouse Gas
GI	Germination Index
GM1	Growing Media 1
GM2	Growing Media 2
GM3	Growing Media 3
GM4	Growing Media 4
GM5	Growing Media 5
GM6	Growing Media 6
GW	Green Waste
GWP	Global Warming Potential
HDS	Honestly Significant Difference
LCA	Life Cycle Assessment
LSD	Least Significant Difference
PD	Particle Density
S	Sediments
TN	Total Nitrogen
TOC	Total Organic Carbon
TPS	Total Pore Space
WBC	Water Buffer Capacity
WC	Water Content

2.1. Growing Mixes

The cultivation trial followed the same scheme reported in [35], using seven different growing mixes (Table 2). The control growing medium (CGM) was a standard commonly used in ornamental plant nurseries composed of peat and pumice (*v*:*v*—1:1). The other substrates were obtained by mixing co-composted dredged sediments (S) and green waste (GW) in different ratios (1:3, 1:1, 3:1) with peat and pumice (GM1, GM2, GM3) or only with themselves (GM4, GM5, GM6). In October 2019, co-composting was carried out outdoors at the certified EPS Biotechnology composting facility located at the biogas plant grounds in Kunovice—Nový Dvůr, Czech Republic (CZ; 49.0060092 N, 17.4904614 E). The sediments were drained locally from a Czech stream, mixed for one week, and sieved (2 mm). Green waste, composed of fresh-cut grass, corn cob biomass, wood chips, and dry leaves, was air-dried separately. The S and GW biomasses were repeatedly homogenized and disintegrated. Finally, all components of each individual compost configuration were mixed and piled by adding urea (1 kg/m^3). The composting process was carried out for about 8 months and co-compost samples were periodically collected and analyzed to assess the development of the process [36].

Table 2. List of the different substrates used in the cultivation phase.

Code	Substrate (in Volume)
CGM	Peat—Pumice (1:1) 100%
GM1	Peat—Pumice (1:1) 50%—dredged sediments—green waste (3:1) 50%
GM2	Peat—Pumice (1:1) 50%—dredged sediments—green waste (1:1) 50%
GM3	Peat—Pumice (1:1) 50%—dredged sediments—green waste (1:3) 50%
GM4	Dredged sediments—green waste (3:1)
GM5	Dredged sediments—green waste (1:1)
GM6	Dredged sediments—green waste (1:3)

2.2. Physical, Chemical, and Biological Analysis of the Co-Composted Material

The substrate samples were sieved to 2 mm and air-dried for chemical and physical analyses, and part of them was also stored at 4 °C for biochemical analyses. Soil bulk density (BD), particle density (PD), total pore space (TPS), air capacity (AC), water content (WC), easily available water (EAW), and water buffer capacity (WBC) were assessed through the pF determination using a sandbox (Royal Eijkelcamp, Giesbeek, The Netherlands) [37]. Specifically, BD was calculated by means of the weight of a dry sample at a known volume. WC was expressed as a percentage by volume at 1 kPa (−10 cm) water pressure and the AC as a percentage by volume (*v*/*v*) with −1 kPa (pressure head). AW was calculated as the difference between the water volume content, expressed as a percentage by volume at a water pressure of −1 kPa (−10 cm) and −10 kPa (−100 cm). The electrical conductivity (EC) and pH were measured after water extraction for 1 h at room temperature, at a ratio of 1:5 (*v*:*v*), using selective electrodes (Conmet 2, Hanna Instruments Italia and Titroprocessor 672, Metrohm, Herisau, Switzerland, respectively) [38,39]. The available nutrients were determined as NH_4^+ and NO_3^- and measured in the water extract using a selective electrode: a GSE ammonia electrode (Sevenmulti, Mettler Toledo, Greifensee, Switzerland) for NH_4^+ and a DX262-NO_3 ISE half-cell electrode (Sevenmulti, Mettler Toledo, Greifensee, Switzerland) for NO_3^- [23]. Total Organic Carbon (TOC) and Total Nitrogen (TN) were detected by dry combustion (temperatures of 950 and 840 °C) using FlashSmart elemental analyzer (Thermo Fisher Scientific, Milan, Italy) equipped with a multi-separation gas chromatographic column (SS; 2 m; 6 × 5 mm). For TOC determination, substrate samples were previously digested using HCl/H_2O (1:1). Hydrolytic enzyme activities were identified using the methods proposed by Marx et al. [40] and Vepsäläinen et al. [41] with fluorogenic methylumbelliferyl (MUF) substrates. The enzymes analyzed were butyrate esterase (EC 3.1.1.1), β-glucosidase (EC 3.2.1.21), acid phosphatase (EC 3.1.3.2), and arylsulphatase (EC 3.1.6.1), using an automated fluorimetric plate-reader (Infinite® F200PRO, Tecan, Männedorf, Switzerland) at 360 nm excitation and 450 nm emission. The germination test was carried out on the water extract (1:5, *v*:*v*) using *Lepidium sativum* seeds following Hoekstra et al.'s method [42].

2.3. Cultivation Phase

One-year-old Fraser Photinia (*P.* × *fraseri* Dress.) and Laurustinus (*V. tinus* L.) plants used in this study were obtained from vegetative propagation. On 15 October 2020, both evergreen shrubs were re-potted from 4 L plastic containers (Ø 18 cm) to 10 L (Ø 24 cm) with growing mixes (see Table 2) added with 4.5 g/L of Basacote® Plus (12M; 15N-15P_2O_5-15K_2O, Compo Expert, Münster, Germany). The cultivation phase lasted 12 months and the plants were placed outdoors in a plant nursery located in Pistoia, following a randomized complete block design. All plants were equally spaced in a metal support grid and drip-irrigated (1 L/pot/day). Weed control was accomplished by covering the pot surface with natural coconut fiber discs. The day before re-potting, 5 plants were randomly selected to estimate values at the beginning of the experiment, while 4 and 3 plants for each substrate were sampled on 1 March 2021 and 15 October 2021, respectively. A total of 108 plants (54 for each species) were used. The parameters measured were plant height and dry weight of above–below-ground biomass. The sampled plants were flared and the roots were washed to remove the growing media. Then, the vegetative material was kept at 80 °C until a constant weight was reached and the final weights were measured by an analytical balance (Sartorius, Göttingen, Germany, ±0.01 g sensitivity).

2.4. Life Cycle Assessment

The environmental analysis was carried out by calculating the equivalent CO_2 emissions (CO_2eq) generated by all the processes taken into consideration. All these emissions, aggregated in a single indicator, represent an increase in Global Warming Potential (GWP), which is defined as "the impact of human emissions on the forced irradiation of the atmosphere" [43]. The GWP was calculated over a 100-year period (GWP 100), in agreement with Shine et al. [44], who consider this indicator as the most suitable, and was also used in the official reports by the United Nation Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). GaBi software (Sphera Solution, Inc., Chicago, IL, USA), updated to its version 10.6.0.110, was employed to perform the LCA analysis, while CML 2001, developed by the University of Leiden, updated to the August 2016 release, was used as the impact characterization method.

2.4.1. System Boundaries and Functional Unit

According to the guidelines contained in the ISO 14044 standard [28] a "gate to gate" approach was adopted in this case study. All the operations and energy inputs needed for the preparation of the different substrates and their ratios (CGM, co-compost, and mixed substrates) and those relating to the cultivation phase were considered (Figure 1). On the other hand, the emissions related to the preliminary cultivation of the repotted plants and those relating to the future fate of the plants at the end of the cultivation trial (e.g., transport, sale, and disposal) were out of the boundary system. Finally, all process emissions that fell within the boundary system were assigned to a functional unit. In our study, one-year-old *V. tinus* or *P.* × *fraseri* plants repotted in a 10 L pot (Ø 24 cm) were chosen as functional units.

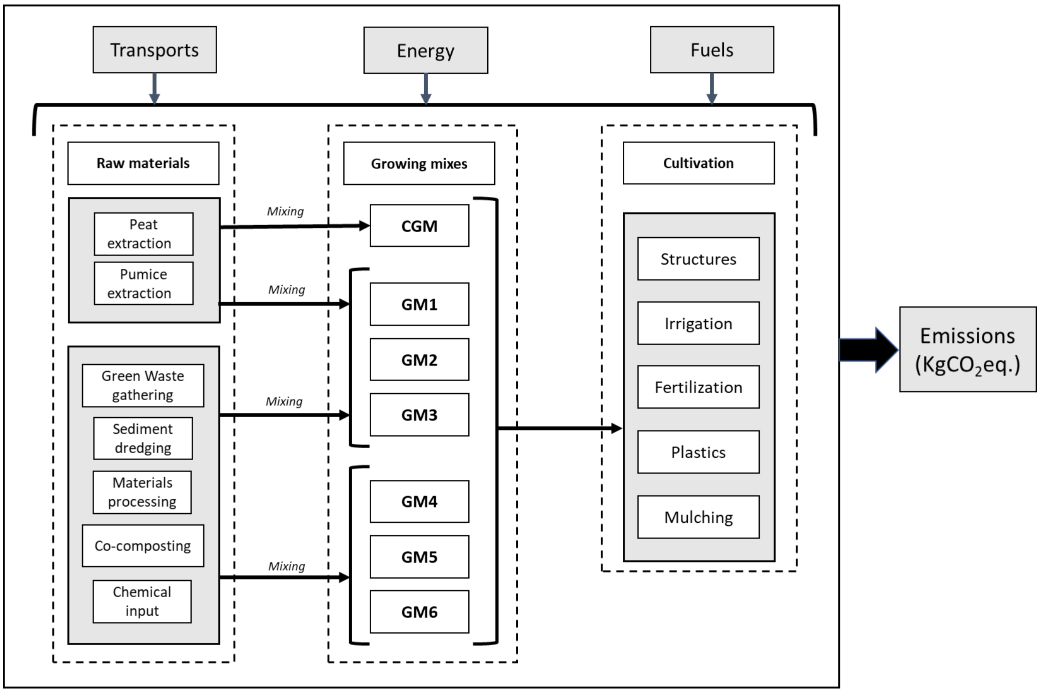

Figure 1. Boundary system of the research carried out in the nursery.

2.4.2. Sediments and Green Waste

The processes considered for the dredged sediment extraction concerning the excavation of the material using a hydraulic backhoe loader and its transport by truck to the "EPS Biotechnology" composting center for 60 km. The emissions generated by green waste were obtained by modeling the following processes used to treat the different materials: a forest chipper for wood chips and a smaller electric chipper for corn crop waste. For grass cuttings, a mower mounted on a tractor was considered and the process of a hydraulic tool mounted on a tractor was modeled for the collection of leaves. For all four components of green waste (wood chips, corn crop waste, grass, and leaves), transport to the composting center was considered. It was carried out by a small van for wood chips, corn residues, and leaves for 90, 30, and 30 km, respectively. Conversely, grass cuttings were transported for 30 km using a trolley coupled to a tractor.

2.4.3. Co-Composting Phase

The emissions due to the process itself were calculated. Co-composting was carried out in a certified facility used for the treatment of compostable material and all operations of homogenization, formation, and management of the heaps being processed were performed using heavy machinery. Finally, the urea input was also accounted for.

2.4.4. Control Growing Media

A growing mix composed of 50% peat and 50% pumice was used as the control treatment. We considered peat extraction in Lithuanian peat bogs and transported it by truck for about 2200 km to the nursery, while for the pumice, an extraction process from an Italian mine and a subsequent road transport for 250 km was modeled. Finally, a shovel excavator was used to mix the substrate. This model was also used for the preparation of substrates consisting of 50% co-compost and 50% control.

2.4.5. Cultivation Phase

The yearly inputs of cultivation, such as fertilization, plastic pots, irrigation, and structures (pumps, pipes, and metal support grid) were considered separately. Impacts were calculated on an annual basis, and a life span of 20 years was defined for the structures. Consequently, the one-year impact of the structures was obtained by dividing the total impact by the number of years.

2.5. Statistical Analyses

The physical, chemical, and biological properties of the growing media were subjected to an analysis of variance (one-way ANOVA). Previously, normal data distribution was tested by the Shapiro–Wilk test. Means were separated by LSD (Least Significant Difference), with a $p \leq 0.05$ level of significance, followed by an HSD (Honestly Significant Difference) Tukey's test. The species-specific relationship of growth parameters (i.e., height, dry weight of above–below ground biomass) with the cultivation time was analyzed by quadratic regression since the residues of a simpler linear regression were not normally distributed. To compare the plant growth at the end of the experiment, the actual sampling days were shifted back by one year [45]. After the shifting, at time zero, the intercept of each quadratic regression can be formally compared against the CGM treatment by a *t*-test. The model space was explored by comparing marginal models. A saturated model was the starting point, which was reduced in the descriptors until no further simplification was allowed. The non-constant variance along time, particularly at the end of the measurements, caused us to include a variance function for modeling heteroscedasticity. All the analyses were performed with R [46] and some of its libraries [47–49]. The details are reported in the Supplementary Materials (Tables S1–S3).

3. Results

3.1. Composting Process

During the composting process, there was a decrease in temperature, gas emissions (CO_2), organic matter content, EC, and microbial activities, as well as an increase in humification rate, as reported by Macci et al. [36].

3.2. Growing Media

The properties of the growing media used in plant cultivation as well as the Italian law limits for mixed growing media [27] are reported in Table 3. Substrates GM1 and GM4, with a 3 S:1 GW compost ratio, showed a TOC below the law limits, while EC was higher in substrates with compost only (GM4, GM5, and GM6). In addition, the BD was higher than the Italian limit for GM6. Both CGM and GM3 showed a concentration of NH^{4+} higher than the other substrates, and a high value of NO_3^- was observed in GM3. All substrates had GI values higher than 100%. The C/N ratio was higher in CGM than in other substrates. Generally, the enzyme activities in GM1, GM2, and GM3 were higher than GM4, GM5, and GM6. In addition, phosphatase and butyrate esterase activities were higher in substrates with a compost ratio of 1 S:3 GW (GM3, GM6) and 1 S:1 GW (GM2, GM5). Arylsulfatase was only detected in the co-composts (GM4, GM5, and GM6) and in the substrates composed of co-compost and peat (GM1, GM2, and GM3).

Table 3. Averaged physical, chemical, and biological properties of the growing media (n = 3). Different letters indicate statistically different values amongst substrates, according to one-way ANOVA followed by HSD Tukey's test ($p \leq 0.05$).

	Substrates							IT Legislation D.Lgs.75/2010
	CGM	**GM1**	**GM2**	**GM3**	**GM4**	**GM5**	**GM6**	**Mixed Media**
BD *	0.3 ± 0.09 a	0.6 ± 0.02 b	0.6 ± 0.05 bc	0.3 ± 0.02 a	0.7 ± 0.02 cd	0.8 ± 0.06 cd	1.0 ± 0.08 d	≤0.95
pH *	4.8 ± 0.1 a	7.0 ± 0.1 bc	7.0 ± 0.1 bc	6.4 ± 0.2 b	6.9 ± 0.5 bc	7.6 ± 0.3 c	7.5 ± 0.2 c	4.5–8.5
EC *	0.3 ± 0.03 a	1.0 ± 0.1 b	1.0 ± 0.1 b	0.5 ± 0.03 a	1.6 ± 0.10 c	1.5 ± 0.17 c	1.6 ± 0.03 c	≤1
NH_4^+	50.8 ± 7.08 b	11 ± 1.21 a	20.0 ± 1.08 a	59.3 ± 1.98 b	12.1 ± 0.49 a	12.4 ± 1.11 a	12.0 ± 1.14 a	
NO_3^-	98.6 ± 0.26 ab	44.1 ± 0.00 a	244 ± 0.40 c	385 ± 40.7 d	141 + 0.08 b	147 ± 0.16 b	157 ± 0.29 b	
TOC *	13 ± 0.92 g	3.7 ± 0.26 c	7.7 ± 0.54 e	10 ± 0.71 f	2.4 ± 0.17 a	4.5 ± 0.32 b	6.6 ± 0.47 d	≥4
TN *	0.4 ± 0.03 b	0.3 ± 0.02 a	0.5 ± 0.03 c	0.5 ± 0.04 c	0.3 ± 0.02 a	0.4 ± 0.03 b	0.7 ± 0.05 d	≤2.5
TOC/TN	36 ± 2.55 d	12 ± 0.85 ab	17 ± 1.21 bc	20 ± 1.40 c	7 ± 0.50 a	11 ± 0.80 a	10 ± 0.71 a	
GI	134 ± 9.8 a	113 ± 12.6 a	145 ± 1.4 a	115 ± 3.9 a	125 ± 8.9 a	110 ± 4.2 a	119 ± 17.6 a	
β-glu	165 ± 32.1 a	443 ± 57.9 bcd	682 ± 102.0 b	510 ± 59.0 cd	217 ± 44.8 ab	171 ± 9.27 a	323 ± 91.5 ac	
Phos	222 ± 15.4 a	532 ± 20.9 d	593 ± 30.8 d	709 ± 22.9 e	269 ± 41.9 ab	329 ± 4.93 bc	369 ± 2.10 c	
But	1092 ± 242.5 a	1910 ± 12.5 cd	2090 ± 91.5 de	2318 ± 192.6 e	1215 ± 103.6 b	1532 ± 82.1 bc	2214 ± 24.1 de	
Aryl	n.d.	76.1 ± 7.5 d	65.3 ± 4.5 cd	52.2 ± 3.6 bc	51.2 ± 2.68 bc	33.1 ± 1.05 a	38.7 ± 1.54 ab	

* Bulk Density (BD; g/cm^3); Total Organic Carbon (TOC, %); EC = electrical conductivity (dS/m); NH_4^+ (mg kg^{-1}); NO_3^- (mg kg^{-1}); Total Nitrogen (TN, %); germination index (GI, %); β-glucosidase (β-glu, mmol MUB kg^{-1} h^{-1}); phosphatase (phos, mmol MUB kg^{-1} h^{-1}); butyrate esterase (but, mmol MUB kg^{-1} h^{-1}); arylsulphatase (aryl, mmol MUB kg^{-1} h^{-1}). * Data published in Macci et al. [26].

3.3. Plant Cultivation Phase

The quadratic regressions used to summarize the experiment showed no statistically significant differences ($p \geq 0.05$) in the intercepts and curvatures of the growing curve for most of the growing variables (plant height and dry weight of above–below ground biomass) for both species (Figure S2). The only exception was the height of *V. tinus*, which showed a simple linear relationship, although not significant, among treatments (see Table S2). A different behavior was observed for the below-ground dry biomass of *V. tinus* only (Table 4 and Figure 2). The GM1 substrate showed a significantly lower growth rate (–0.104 g per day, p = 0.0174), which yielded a final value of 37.184 g less than that of CGM (p = 0.0112). In addition, GM5 showed a similar reduced final value (–28.578 g), but with a slightly different significance (p = 0.049) and a growth rate very close to statistical significance (–0.079 g per day, p = 0.0680).

Table 4. The first line (intercept) is the mean of below-ground dry biomass achieved by *V. tinus* plant growth on CGM substrate, while lines 2–7 refer to the difference against CGM at the end of the experiment. Lines DAYS and $DAYS^2$ ($p < 1 \times 10^{-3}$) indicate the linear and quadratic terms of CGM, respectively. The subsequent lines are the differences between each substrate and CGM in the linear term of the regression. The graphic results are depicted in Figure 2.

	Below-Ground Dry Biomass (g)	Std. Error	*t*-Value	*p*-Value
(Intercept)	143.034	10.3718	13.7907	$<1 \times 10^{-3}$
GM1	−37.184	14.2611	−2.6074	0.0112
GM2	−16.528	14.2611	−1.1589	0.2505
GM3	−12.948	14.2611	−0.9079	0.3671
GM4	−22.004	14.2611	−1.5429	0.1274
GM5	−28.578	14.2611	−2.0039	0.0490
GM6	21.506	14.2611	1.5080	0.1361
DAYS	0.637	0.0523	12.1627	$<1 \times 10^{-3}$

Table 4. *Cont.*

	Below-Ground Dry Biomass (g)	Std. Error	*t*-Value	*p*-Value
$DAYS^2$	0.001	0.0001	8.5705	$<1 \times 10^{-3}$
GM1:DAYS	−0.104	0.0427	−2.4380	0.0174
GM2:DAYS	−0.046	0.0427	−1.0734	0.2868
GM3:DAYS	−0.038	0.0427	−0.8774	0.3833
GM4:DAYS	−0.060	0.0427	−1.4021	0.1654
GM5:DAYS	−0.079	0.0427	−1.8543	0.0680
GM6:DAYS	0.057	0.0427	1.3333	0.1868

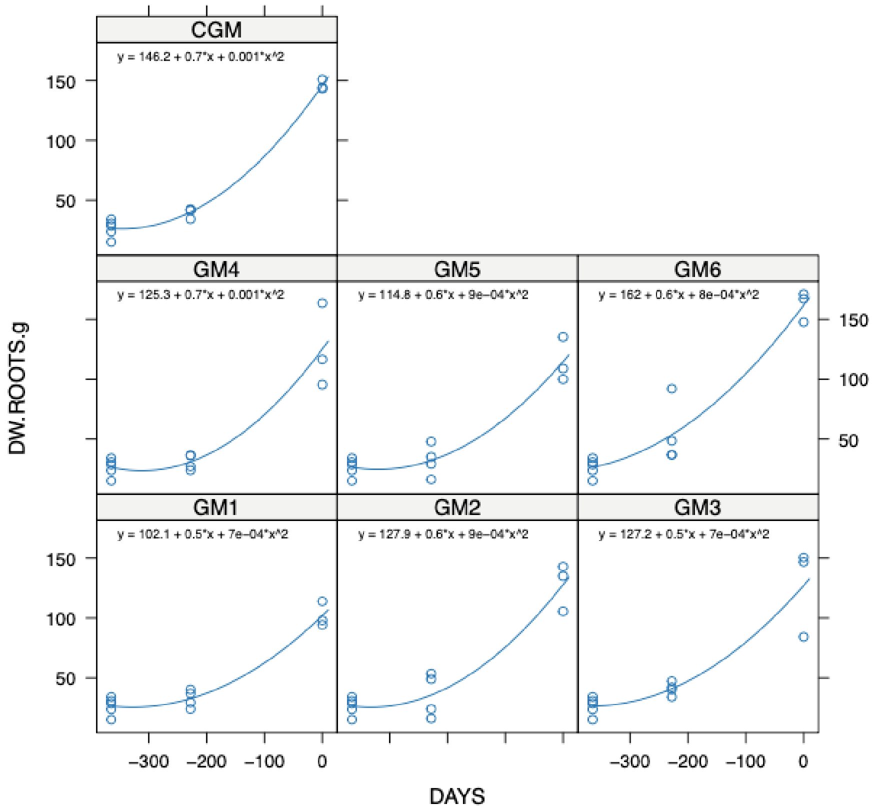

Figure 2. Dry below-ground biomass growth curves of *V. tinus* are described by a quadratic regression for each substrate. To compare the plant growth at the end of the experiment, the actual sampling days were shifted back by one year. Formal analysis results are reported in Table 4.

3.4. Life Cycle Assessment

3.4.1. Peat–Pumice Control Substrate

Substrates composed of peat and pumice in a 1:1 ratio involved emissions equal to 0.57 kg CO_2eq for annual production in a single 10 L potted plant, as shown in Figure 3. Most of the impact is clearly due to peat, mainly from its extraction (0.39 kg CO_2eq/plant) and secondarily from its transport (0.14 kg CO_2eq/plant). In fact, these two factors alone represent almost 93% of the total emissions, while the extraction (0.01 kg CO_2eq/plant) and transport (0.02 kg CO_2eq/plant) of the pumice as well as the preparation of the substrate (0.01 kg CO_2eq/plant) had very low emissions, with 1.75% (pumice extraction), 3.51% (pumice transport), and 1.75% (substrate mixing).

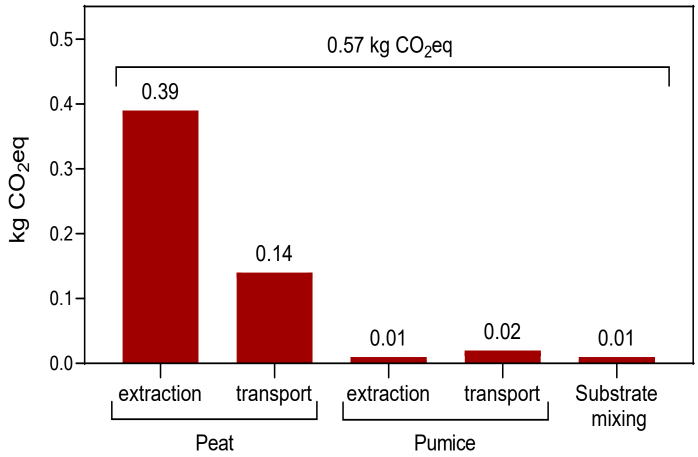

Figure 3. Peat–pumice control growing medium emissions (kg CO_2eq) per single plant grown in a 10 L pot.

3.4.2. Co-Composted Materials

CO_2 emissions linked to the co-composting process were calculated for the three types of substrates obtained (Figure 4). The entire composting phase represented the most impactful input, a constant value (0.13 kg CO_2eq/plant) for all three composts, while the impact due to the use of S and GW changed according to the different component ratios. However, as can be observed in the GM5 substrate, with a 1 S:1 GW ratio, a higher level of emissions was detected for GW; S showed 0.04 kg CO_2eq/plant for a single plant, against 0.06 for GW. Consequently, 1 S:3 GW (0.25 kg CO_2eq/plant) showed the greatest impact followed by 1 S:1 GW (0.23 kg CO_2eq/plant) and 3 S:1 GW (0.22 kg CO_2eq/plant).

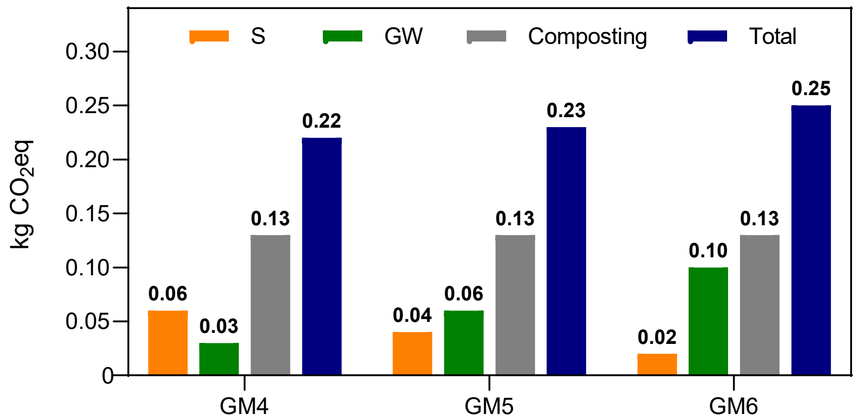

Figure 4. Co-composted substrates emissions (kg CO_2eq) per single plant grown in a 10 L pot.

3.4.3. Cultivation Phase

The CO_2eq emission factors for the cultivation phase are shown in Figure 5. Plastic pots, made with high-density polyethylene, represented by far the highest emission source, with 0.56 kg CO_2eq/plant (more than 62% of the total impact), followed by nursery structures, such as plastic pipes for irrigation and metal support grids (18% and 11% of total emissions, respectively). The remaining impacts were due to the energy used for irrigation pumps (4.4%), production and use of fertilizers (3.3%), and use of coconut fiber mulching discs (1.1%).

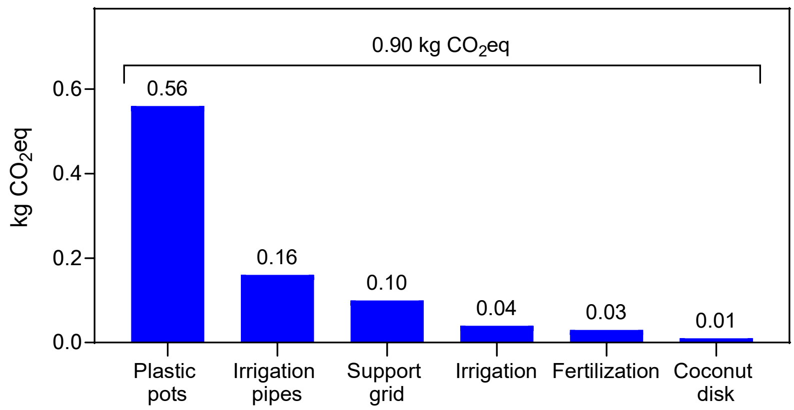

Figure 5. Cultivation phase emissions (kg CO_2eq) per single plant grown in a 10 L pot.

3.4.4. Total Emissions

The LCA results showed a general decrease in GHG emissions associated with the production of ornamental plants in containers after completely or partially replacing the peat–pumice substrate with a co-composted material based on dredged sediments and green waste (Table 5). The impact of the various inputs of cultivation was considered together with the impact of the different substrates tested in this study. Cultivation in the control substrate (CGM) was the most impactful, with 1.47 kg CO_2eq for each plant produced. The three substrates where CGM was mixed with the various composted matrices (GM1, GM2, GM3) showed a reduced emission level, ranging from 1.30 kg CO_2eq for plants grown in 3 S:1 GW to 1.32 kg CO_2eq for the ones with 1 S:3 GW. GM4, GM5, and GM6 were the less impactful substrates with an emission per single plant equal to 1.12, 1.13, and 1.15 kg CO_2eq/plant, respectively.

Table 5. GHG emissions related to the different inputs involved in the production of the growing mix tested (kg CO_2eq).

Input	CGM	GM1	GM2	GM3	GM4	GM5	GM6
Sediments							
Excavation		0.005	0.003	0.002	0.01	0.005	0.003
Transport		0.025	0.018	0.009	0.05	0.035	0.017
Green Waste							
Gathering and processing		0.013	0.026	0.043	0.026	0.051	0.086
Transport		0.002	0.005	0.007	0.004	0.009	0.014
Composting							
Composting site		0.020	0.020	0.020	0.04	0.04	0.04
Heaps handling		0.040	0.040	0.040	0.08	0.08	0.08
Urea		0.005	0.005	0.005	0.01	0.01	0.01
Control substrate							
Peat extraction	0.39	0.20	0.20	0.20			
Peat transport	0.14	0.07	0.07	0.07			
Pumice extraction	0.01	0.005	0.005	0.005			
Pumice transport	0.02	0.01	0.01	0.01			
Mixing	0.01	0.005	0.005	0.005			
Cultivation							
Plastic pot	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Plastic pipings	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Structures	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Fertilization	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Mulching	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Irrigation	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Total emissions	1.47	1.30	1.31	1.32	1.12	1.13	1.15

4. Discussion

Generally, the results showed that the physical and chemical properties of growing media are suitable for plant growth, in line with Italian legislation [27], with some exceptions (i.e., GM4-5-6) (see Figure S3). However, the addition of peat as a source of organic matter to co-composts allowed us to reach Italian law limits [26]. In fact, the presence of 50% peat reduced the EC and BD as well as increased the TOC in the co-composts. The high NO_3^- concentrations in the substrates composed of co-compost and peat could be related to the increase in pH; in fact, nitrification in peat is limited because of the acidic pH [50]. In addition, the lower C/N in the substrates composed of co-compost compared to peat suggested nitrogen mineralization and a higher availability of nitrogen for plant uptake [51]. In all substrates, a GI > 100% indicates the absence of phytotoxicity and the presence of nutrients that stimulate seed germination and seedling root elongation. Enzyme activities are often used as indicators of soil health (in this case, growing media) and nutrient cycles [52]. In particular, the addition of peat to co-composts improved the microbial activities, as measured by the butyrate esterase assay [53], as well as the enzymes related to the C (β-glucosidase), S (arylsulfatase), and P (phosphatase) cycles. In addition, the combination of peat and co-composts in the growing media enhanced arylsulfatase activity, which was not detected in peat. In fact, the high content of organo-sulfur molecules in the sediment and the high organic matter in peat stimulates enzyme activities involved in sulfate release [54,55].

The cultivation trial carried out for *P.* × *fraseri* did not highlight any statistically significant difference in the plant growth parameters for any treatment when compared to the standard substrate (CGM). However, it is interesting to underline that plants grown on substrates entirely made up of compost (GM4, GM5, GM6), despite their chemical-physical properties, did not fully comply with the Italian legislative standard [27] and did not show substantial growth differences compared to the other substrates. Our results are consistent with those of Mattei et al. [56], where differences in plant elongation were not detected at the end of the growing period in *P.* × *fraseri* seedlings cultivated in co-composted substrates rather than in the peat and pumice control mix (ratio 1:1). Furthermore, for *V. tinus*, the measured parameters (height and above-/below-ground dry biomass) did not show any statistical difference among the plants grown in different media with exception of the root apparatus in GM1 and GM5. Nevertheless, these differences observed in the Laurustinus plants did not alter their total growth (above- and below-ground biomass, data not shown), confirming overall balanced plant development and their marketability regardless of the substrates tested. Furthermore, the same growth results in terms of plant height and above-ground biomass were obtained in a different experimental scenario, with our target species cultivated for two years in the field adding dredged sediments to alluvial soil [21]. Nin et al. [23] also reported that there were no differences in maximum plant height over time in another evergreen shrub (i.e., *Prunus laurocerasus*) grown on similar substrates.

From an environmental point of view, LCA analysis allowed us to estimate the CO_2eq emissions linked to both the production of substrates and the subsequent cultivation phase. The standard peat–pumice growing mix (CGM) was confirmed to be the most impactful substrate because of the extraction and transport of peat, as stated by Lazzerini et al. [5,57]. On the other hand, as confirmed in a previous study [58], the use of waste by-products in growing mixtures led to lower total emissions of CO_2eq into the atmosphere. In fact, as shown in Figure 6, the use of composted materials (GM4-5-6) resulted in an average reduction in emissions of 23.13% compared to the standard cultivation substrates. The percentage value drops to an average of 11.56% if the substrates made by compost and control substrate in a 1:1 ratio (GM1-2-3) are considered. However, if we exclude the emissions generated by the cultivation phase, which alone involves a constant release of 0.9 kg CO_2eq/plant for all the treatments, the above percentages increase to 28.1% (GM1-2-3) and 59.1% (GM4-5-6). These results are not in agreement with those of other studies on the use of sediments in horticulture, where these matrices showed an impact in terms of kg CO_2eq greater than peat-based substrates [59,60]. However, this was explained by the fact that a different functional unit based on production (i.e., 1 kg of fruit) was employed. In fact, lower yields were obtained with plants grown on sediment-based substrates, leading to a higher environmental impact per product unit. In contrast, our research, based on ornamentals, had a single potted plant produced as an impact reference, thus avoiding any connection with fruit productivity.

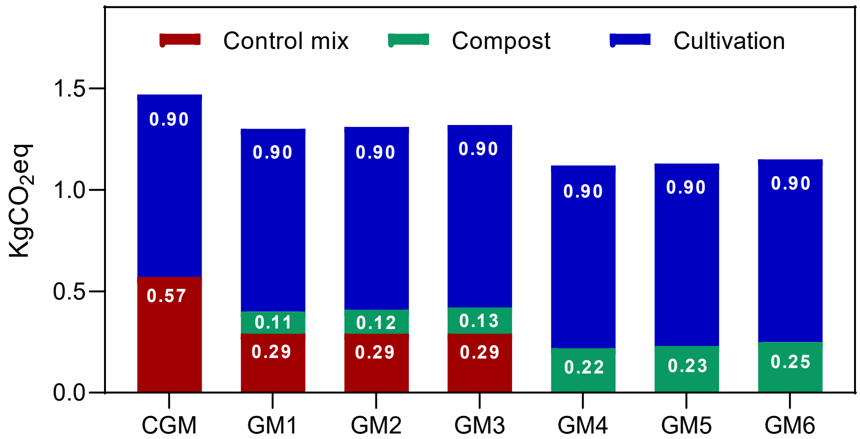

Figure 6. Total emissions (kg CO_2eq) for all substrates used in the trial per single plant grown in a 10 L pot.

Finally, it should also be underlined that more than 60% of this impact is due to the sole use of plastic pots, in line with results obtained in previous studies [5,57].

5. Conclusions

Our findings highlighted some interesting potential of the tested substrates in terms of the technical aspects inherent in ornamental plant cultivation (i.e., growth), allowing CO_2 savings at the same time. Nevertheless, we tested two hardy evergreen shrubs, relatively easy to manage in a plant nursery. Further studies are needed to verify the suitability of these by-products for the cultivation of species more sensitive to substrates, or young propagated plants, which are usually more demanding in terms of production inputs. Consequently, it could be appropriate to maintain peat in potting mix formulations as a diluent to compensate for the less favorable characteristics of these alternative substrates, as stated by Schmilewski [8]. The results of environmental impact analyses increase the awareness of policymakers about the benefits of reducing the exploitation of natural resources and GHG emission control. However, replacing the peat input, which requires the extraction and transport for thousands of kilometers, with locally available by-products is a crucial step, opening new perspectives to improve the sustainability of the ornamental nursery sector. Further action will also be needed for the environmental sustainability of this production chain in developing alternatives to plastic pots, a very significant source of CO_2eq emissions.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app14041538/s1, Table S1: ANOVA analysis on marginal models describing plant growth parameters. Table S2: Summaries of the models used to compare the growths of plants cultivated on different substrates. Table S3: Row data of *P.* × *fraseri* and *V.tinus* growth parameters for different substrates. Figure S1: Flowchart of the Materials and Methods Section 2. Figure S2: Relationship between time and growth parameters as influenced by different substrates. Figure S3: *P.* × *fraseri* and *V. tinus* plants grown with different substrates at the end of the cultivation phase.

Author Contributions: F.P.N., L.A., J.M. and S.L. conceived the study; L.A. carried out the LCA analysis and data collection; O.L.P. performed the regression analysis; C.M., F.V., G.M. and P.A. performed substrate analyses. All authors were involved in writing the paper, although F.P.N., L.A.

and J.M. took a lead role. S.I.P. and G.P. reviewed and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author Stefano Lucchetti was employed by the company Agri Vivai S.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Gabellini, S.; Scaramuzzi, S. Evolving consumption trends, marketing strategies, and governance settings in ornamental horticulture: A grey literature review. *Horticulturae* **2022**, *8*, 234. [CrossRef]
2. Chong, C. Experiences with wastes and composts in nursery substrates. *HortTechnology* **2005**, *15*, 739–747. [CrossRef]
3. Salachna, P. Trends in Ornamental Plant Production. *Horticulturae* **2022**, *8*, 413. [CrossRef]
4. EU Commission. Flowers and ornamental plants production. Statistics 2010–2019. 2019. Available online: https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/plants_and_plant_products/documents/flowers-ornamental-plants-statistics_en.pdf (accessed on 6 February 2023).
5. Lazzerini, G.; Lucchetti, S.; Nicese, F.P. GHG emissions from ornamental plants nursery industry: A LCA approach in Pistoia nursery district. *J. Clean. Prod.* **2016**, *112*, 4022–4030. [CrossRef]
6. Bohlin, C.; Holmberg, P. Peat: Dominating growing medium in Swedish horticulture. *Int. Symp. Grow. Media Hydroponics* **2001**, *644*, 177–181. [CrossRef]
7. Ostos, J.C.; López-Garrido, R.; Murillo, J.M.; López, R. Substitution of peat for municipal solid waste-and sewage sludge-based composts in nursery growing media: Effects on growth and nutrition of the native shrub *Pistacia lentiscus* L. *Bioresour. Technol.* **2008**, *99*, 1793–1800. [CrossRef] [PubMed]
8. Schmilewski, G. Producing growing media responsibly to help sustain horticulture. *Int. Symp. Grow. Media Soil. Cultiv.* **2013**, *1034*, 299–306. [CrossRef]
9. Kitir, N.; Yildirim, E.; Şahin, Ü.; Turan, M.; Ekinci, M.; Ors, S.; Kul, R.; Ünlü, H.; Ünlü, H. Peat use in horticulture. In *Peat*; IntechOpen: Rijeka, Croatia, 2018; pp. 76–79. [CrossRef]
10. Jurasinski, G.; Ahmad, S.; Anadon-Rosell, A.; Berendt, J.; Beyer, F.; Bill, R.; Blume-Werry, G.; Couwenberg, J.; Günther, A.; Joosten, H.; et al. From Understanding to Sustainable Use of Peatlands: The WETSCAPES Approach. *Soil. Syst.* **2020**, *4*, 14. [CrossRef]
11. Alexander, P.D.; Bragg, N.C.; Meade, R.; Padelopoulos, G.; Watts, O. Peat in Horticulture and Conservation: The UK Response to a Changing World. Available online: http://pixelrauschen.de/wbmp/media/map03/map_03_08.pdf (accessed on 8 February 2023).
12. De Lucia, B.; Vecchietti, L.; Rinaldi, S.; Rivera, C.M.; Trinchera, A.; Rea, E. Effect of peat-reduced and peat-free substrates on rosemary growth. *J. Plant Nutr.* **2013**, *36*, 863–876. [CrossRef]
13. Abad, M.; Noguera, P.; Bures, S. National inventory of organic wastes for use as growing media for ornamental potted plant production: Case study in Spain. *Bioresour. Technol.* **2001**, *77*, 197–200. [CrossRef]
14. Bilderback, T.E.; Riley, E.D.; Jackson, B.E.; Kraus, H.T.; Fonteno, W.C.; Owen Jr, J.S.; Atland, J.; Fain, G.B. Strategies for developing sustainable substrates in nursery crop production. *Acta Hortic.* **2013**, *1013*, 43–56. [CrossRef]
15. Barrett, G.E.; Alexander, P.D.; Robinson, J.S.; Bragg, N.C. Achieving environmentally sustainable growing media for soilless plant cultivation systems–A review. *Sci. Hortic.* **2016**, *212*, 220–234. [CrossRef]
16. Chrysargyris, A.; Stavrinides, M.; Moustakas, K.; Tzortzakis, N. Utilization of paper waste as growing media for potted ornamental plants. *Clean. Technol. Environ. Policy* **2019**, *21*, 1937–1948. [CrossRef]
17. Urrestarazu, M.; Mazuela, P.C.; Martínez, G.A. Effect of substrate reutilization on yield and properties of melon and tomato crops. *J. Plant Nutr.* **2008**, *31*, 2031–2043. [CrossRef]

18. Mariotti, B.; Martini, S.; Raddi, S.; Tani, A.; Jacobs, D.F.; Oliet, J.A.; Maltoni, A. Coconut Coir as a Sustainable Nursery Growing Media for Seedling Production of the Ecologically Diverse Quercus Species. *Forests* **2020**, *11*, 522. [CrossRef]
19. Di Lonardo, S.; Cacini, S.; Becucci, L.; Lenzi, A.; Orsenigo, S.; Zubani, L.; Rossi, G.; Zaccheo, P.; Massa, D. Testing new peat-free substrate mixtures for the cultivation of perennial herbaceous species: A case study on Leucanthemum vulgare Lam. *Sci. Hortic.* **2021**, *289*, 110472. [CrossRef]
20. Mattei, P.; Pastorelli, R.; Rami, G.; Mocali, S.; Giagnoni, L.; Gonnelli, C.; Renella, G. Evaluation of dredged sediment co-composted with green waste as plant growing media assessed by eco-toxicological tests, plant growth and microbial community structure. *J. Hazard. Mater.* **2017**, *333*, 144–153. [CrossRef] [PubMed]
21. Ugolini, F.; Calzolari, C.; Lanini, G.M.; Massetti, L.; Pollaki, S.; Raschi, A.; Sabatini, F.; Tagliaferri, G.; Ungaro, F.; Massa, D.; et al. Testing decontaminated sediments as a substrate for ornamentals in field nursery plantations. *J. Environ. Manag.* **2017**, *197*, 681–693. [CrossRef] [PubMed]
22. Renella, G. Recycling and reuse of sediments in agriculture: Where is the problem? *Sustainability* **2021**, *13*, 1648. [CrossRef]
23. Nin, S.; Bonetti, D.; Antonetti, M.; Peruzzi, E.; Manzi, D.; Macci, C. Sediment-Based Growing Media Provides a Window Opportunity for Environmentally Friendly Production of Ornamental Shrubs. *Agronomy* **2022**, *13*, 92. [CrossRef]
24. Vannucchi, F.; Macci, C.; Doni, S.; Longo, V.; Ugolini, F.; Masciandaro, G.; Peruzzi, E. Posidonia-Based Compost and Dredged Sediment in Growing Media Improve Tolerance and Nutrient Uptake in Ornamental Plants. *Sustainability* **2022**, *14*, 14419. [CrossRef]
25. Mattei, P.; Cincinelli, A.; Martellini, T.; Natalini, R.; Pascale, E.; Renella, G. Reclamation of river dredged sediments polluted by PAHs by co-composting with green waste. *Sci. Total Environ.* **2016**, *566*, 567–574. [CrossRef]
26. Macci, C.; Vannucchi, F.; Doni, S.; Peruzzi, E.; Lucchetti, S.; Castellani, M.; Masciandaro, G. Recovery and environmental recycling of sediments: The experience of CNR-IRET Pisa. *J. Soils Sediments* **2022**, *22*, 1–8. [CrossRef]
27. D.lgs 75/2010. Decreto Legislativo 75/2010. Reorganization and Review of the Fertilizer Regulations (Riordino e Revisione della Disciplina in Materia di Fertilizzanti). Available online: https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/10087 (accessed on 26 January 2023).
28. *EN ISO 14044*; Environmental Management–Life Cycle Assessment–Requirements and Guidelines. International Standards Authority (ISO): Corona, CA, USA, 2018. Available online: https://www.scopus.com/record/display.uri?eid=2-s2.0-85094861905&origin=inward (accessed on 26 January 2023).
29. Casey, J.W.; Holden, N.M. Quantification of GHG emissions from sucker-beef production in Ireland. *Agric. Syst.* **2006**, *90*, 79–98. [CrossRef]
30. Williams, A.G.; Audsley, E.; Sandars, D.L. Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. In *Main Report, Defra Research Project IS0205*; Cranfield University and Defra: Cranfield, UK, 2006; Available online: http://www.defra.go.uk (accessed on 25 September 2008).
31. Black, M.J.; Whittaker, C.; Hosseini, S.A.; Diaz-Chavez, R.; Woods, J.; Murphy, R.J. Life Cycle Assessment and sustainability methodologies for assessing industrial crops, processes and end products. *Ind. Crops Prod.* **2011**, *34*, 1332–1339. [CrossRef]
32. Frankowska, A.; Jeswani, H.K.; Azapagic, A. Environmental impacts of vegetables consumption in the UK. *Sci. Total Environ.* **2019**, *682*, 80–105. [CrossRef] [PubMed]
33. Eady, S.; Carre, A.; Grant, T. Life cycle assessment modelling of complex agricultural systems with multiple food and fibre co-products. *J. Clean. Prod.* **2012**, *28*, 143–149. [CrossRef]
34. Warner, D.J.; Davies, M.; Hipps, N.; Osborne, N.; Tzilivakis, J.; Lewis, K.A. Greenhouse gas emissions and energy use in UK-grown short-day strawberry (Fragaria x ananassa Duch) crops. *J. Agric. Sci.* **2010**, *148*, 667–681. [CrossRef]
35. Arfaioli, P.; Azzini, L.; Cincinelli, A.; Heřmánková, M.; Lucchetti, S.; Macci, C.; Masciandaro, G.; Scodellini, R.; Renella, G.; Waska, K.; et al. Waste materials-based substrates for ornamental plant production: Technical and environmental aspects. *II Int. Symp. Grow. Media Soil. Cultiv. Compos. Util. Hortic.* **2021**, *1317*, 79–86. [CrossRef]
36. Macci, C.; Vannucchi, F.; Peruzzi, E.; Doni, S.; Lucchetti, S.; Waska, K.; Heřmánková, M.; Scodellini, R.; Cincinelli, A.; Nicese, F.P.; et al. A low impact sediment and green waste co-compost: Can it replace peat in the nursery sector? *Environ. Dev. Sustain.* **2023**, 1–28. [CrossRef]
37. *EN 13041: 2011*; Soil Improvers and Growing Media–Determination of Physical Properties–Dry Bulk Density, Air Volume, Water Volume, Shrinkage Value and Total Pore Space. European Committee for Standardization: Brussels, Belgium, 2011.
38. *EN 13038:2012*; Soil Improvers and Growing Media-Determination of Electrical Conductivity. European Committee for Standardization: Brussels, Belgium, 2012.
39. *EN 13037:2011*; Soil Improvers and Growing Media-Determination of pH. European Committee for Standardization: Brussels, Belgium, 2011.
40. Marx, M.C.; Wood, M.; Jarvis, S.C. A microplate fluorimetric assay fir the study of enzyme diversity in soils. *Soil Biol. Biochem.* **2001**, *33*, 1633–1640. [CrossRef]
41. Vepsäläinen, M.; Kukkonen, S.; Vestberg, M.; Sirviö, H.; Niemi, R.M. Application of soil enzyme activity test kit in a field experiment. *Soil Biol. Biochem.* **2011**, *33*, 1665–1672. [CrossRef]
42. Hoekstra, N.J.; Bosker, T.; Lantinga, E.A. Effects of cattle dung from farms with different feeding strategies on germination and initial root growth of cress (*Lepidium sativum* L.). *Agric. Ecosyst. Environ.* **2002**, *93*, 189–196. [CrossRef]

43. Guinée, J.B.; Lindeijer, E. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2002. [CrossRef]
44. Shine, K.P.; Fuglestvedt, J.S.; Hailemariam, K.; Stuber, N. Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Clim. Change* **2005**, *68*, 281–302. [CrossRef]
45. Pinheiro, J.C.; Bates, D.M. Linear mixed-effects models: Basic concepts and examples. In *Mixed-Effects Models in S and S-Plus*; Springer: Berlin/Heidelberg, Germany, 2000; pp. 3–56. [CrossRef]
46. *R Core Team R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2023.
47. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D. *R Core Team Nlme: Linear and Nonlinear Mixed Effects Models 2023*; R Foundation for Statistical Computing: Vienna, Austria, 2023.
48. Sarkar, D. *Lattice: Multivariate Data Visualization with R*; Springer: New York, NY, USA, 2008. [CrossRef]
49. Wickham, H. The Split-Apply-Combine Strategy for Data Analysis. *J. Stat. Softw.* **2011**, *40*, 1–29. [CrossRef]
50. Paillat, L.; Cannavo, P.; Barraud, F.; Huché-Thélier, L.; Guénon, R. Growing medium type affects organic fertilizer mineralization and CNPS microbial enzyme activities. *Agronomy* **2020**, *10*, 1955. [CrossRef]
51. Gerald, E. Chapter 9—Management Strategies for Organic Vegetable Fertility. In *Micallef, Safety and Practice for Organic Food*; Biswas, D., Shirley, A., Eds.; Academic Press: New York, NY, USA, 2019; pp. 193–212. [CrossRef]
52. Burns, R.; DeForest, J.; Marxsen, J.; Sinsabaugh, R.; Stromberger, M.; Wallenstein, M.; Weintraub, M.; Zoppini, A. Soil enzymes in a changing environment: Current knowledge and future directions. *Soil. Biol. Biochem.* **2013**, *58*, 216–234. [CrossRef]
53. Wittmann, C.; Kähkönen, M.A.; Ilvesniemi, H.; Kurola, J.; Salkinoja-Salonen, M.S. Areal activities and stratification of hydrolytic enzymes involved in the biochemical cycles of carbon, nitrogen, sulphur and phosphorus in podsolized boreal forest soils. *Soil. Biol. Biochem.* **2004**, *36*, 425–433. [CrossRef]
54. Wasmund, K.; Mußmann, M.; Loy, A. The life sulfuric: Microbial ecology of sulfur cycling in marine sediments. *Environ. Microbiol. Rep.* **2017**, *9*, 323–344. [CrossRef]
55. Chang, E.; Chung, R.; Tsai, Y. Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population. *Soil. Sci. Plant Nutr.* **2007**, *53*, 132–140. [CrossRef]
56. Mattei, P.; D'Acqui, L.P.; Nicese, F.P.; Lazzerini, G.; Masciandaro, G.; Macci, C.; Doni, S.; Sarteschi, F.; Giagnoni, L.; Renella, G. Use of phytoremediated sediments dredged in maritime port as plant nursery growing media. *J. Environ. Manag.* **2017**, *186*, 225–232. [CrossRef]
57. Lazzerini, G.; Manzini, J.; Lucchetti, S.; Nin, S.; Nicese, F.P. Greenhouse Gas Emissions and Carbon Sequestration from Conventional and Organic Olive Tree Nurseries in Tuscany, Italy. *Sustainability* **2022**, *14*, 16526. [CrossRef]
58. Boldrin, A.; Hartling, K.R.; Laugen, M.; Christensen, T.H. Environmental inventory modelling of the use of compost and peat in growth media preparation. *Resour. Conser. Recycl.* **2010**, *54*, 1250–1260. [CrossRef]
59. Legua, P.; Hernández, F.; Tozzi, F.; Martínez-Font, R.; Jorquera, D.; Rosique Jiménez, C.; Giordani, E.; Martínez-Nicolás, J.J.; Melgarejo, P. Application of LCA Methodology to the Production of Strawberry on Substrates with Peat and Sediments from Ports. *Sustainability* **2021**, *13*, 6323. [CrossRef]
60. Hernández, F.; Martínez-Nicolás, J.J.; Melgarejo, P.; Núñez-Gómez, D.; Lidón, V.; Martínez-Font, R.; Legua, P. Life Cycle Assessment (LCA) of Substrate Mixes Containing Port Sediments for Sustainable 'Verna'Lemon Production. *Foods* **2022**, *11*, 3053. [CrossRef]