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# Comparative environmental and economic life cycle assessment of phytoremediation of dredged sediment using *Arundo Donax*, integrated with biomass to bioenergy valorization chain

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1 **Comparative environmental and economic Life Cycle Assessment of phytoremediation**  
2 **of dredged sediment using *Arundo Donax*, integrated with biomass to bioenergy**  
3 **valorization chain**

4  
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7  
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11  
12  
13 **Abstract**

14 The economic and environmental life cycle assessment (LCA) was integrated into a  
15 laboratory-based experiment to evaluate the feasibility and sustainability of phytoremediation  
16 of chloride-rich marine dredged sediment, using perennial reed *Arundo Donax* along with  
17 biomass valorization. As a prerequisite for life cycle assessments, a baseline mathematical  
18 model was developed to estimate the yields of biomass to bioenergy valorization chain  
19 including the estimation of biomass yield per m<sup>3</sup> sediment, bioenergy yields from valorization  
20 schemes, expected green electricity yield, and the phytoremediation time frame. This  
21 mathematical model was applied to develop a parametric life cycle inventory for two  
22 scenarios of sediment phytoremediation separately or integrated with biomass valorization,  
23 for LCA and further sensitivity and uncertainty analysis. Comparative LCA unveiled that the  
24 cost and environmental impacts of annual phytoremediation of 1m<sup>3</sup> sediment alone or  
25 integrated with biomass valorization are much inferior to the corresponding sediment landfill  
26 as the inevitable alternative approach for sediment management. With the chloride  
27 bioaccumulation capacity of 9940 mg per kg dry biomass of *A. donax*, the phytoremediation

28 of sediment with chloride concentration higher than 1650 mg/kg may not be achievable in a  
29 realistic time frame. Due to the importance of considering sediment depth and the  
30 effectiveness of the plant rooting system in estimating the performance of phytoremediation  
31 and the time frame, the volume of sediment ( $1\text{m}^3$ ) is a more appropriate functional unit than  
32 the surface area (ha) for LCA studies of phytoremediation. In addition, considering the  
33 volume of sediment as a functional unit retains comparability to other valorization scenarios  
34 such as sediment incorporation in cementitious matrices and management scenarios such as  
35 landfill, which are generally expressed on a volume or mass basis. Integrating biomass-  
36 derived bioenergy production into phytoremediation could offer local and global benefits in  
37 terms of economy and environment mainly due to carbon sequestration and avoiding fossil-  
38 based fuels.

39

40 **Keywords:** *Arundo donax*, life cycle assessment, chloride-rich marine dredged sediment,  
41 Biomass to bioenergy valorization, phytoremediation

42

### 43 **1. Introduction**

44

45 As a worldwide issue in terms of economy and environment, the million tons of annually  
46 dredged sediments must be managed to satisfy the gradually stricter regulatory requirements.  
47 According to French regulations, the discharge of polluted sediments and dredging residues  
48 into the sea would be prohibited from 2025 (legifrance, 2016). The non-inert dredged  
49 sediment carried to land should be treated via remediation, valorization, landfill, or combined  
50 approaches. Along with the conventional physicochemical remediation technologies which  
51 are very costly for sediment with a zero-market value and may not be feasible on a large  
52 scale, the passive treatment of phytoremediation has been identified as a cost-effective, eco-  
53 friendly, solar-driven and in-situ technology for bio-remediation of contaminated sediment

54 (Zaghloul, 2020). The process consists of using plants and their associated micro-organisms  
55 to reduce contamination from a given media by uptake and bioaccumulation (Pirzadah et al.,  
56 2015). The long-term time frame and lack of revenue from the land during the remediation  
57 process are the major bottlenecks of phytoremediation for further popularity and  
58 development. To alleviate these limitations, phytomanagement emerged from integrating  
59 biomass valorization into phytoremediation (Nascimento et al., 2021). Phytomanagement of  
60 dredged sediment, under the concepts of circular economy, could synergize biomass  
61 production and carbon sequestration with phytoremediation, offering social, economic, and  
62 environmental benefits during the whole remediation process up to inert and productive  
63 sediment (Nascimento et al., 2021).

64 Two general types of hyperaccumulator and high-yielding biomass plants could be applied for  
65 in-situ phytoremediation of dredged sediment to reduce the targeted contaminants to  
66 regulatory levels. The proper plant species for sediment phytoremediation could be selected  
67 from a compromise between the plant accumulation rate of target element, growth rate,  
68 biomass production capacity, biodiversity, tolerance to high concentrations of accumulated  
69 elements and salinity of sediment (Rabêlo et al., 2021). Since dredged sediments are generally  
70 multi-element contaminated, the hyperaccumulator plants may not be tolerant to multiple  
71 inorganic compounds such as heavy metals (Nascimento et al., 2021). *Arundo Donax*  
72 (*A. donax*), a high-yielding perennial reed, highly efficient resource utilization, tolerant to  
73 biotic, abiotic and salinity stresses, trace elements and chemical composition of sediment has  
74 been applied for phytoextraction of pollutants along with the production of marketable  
75 biomass (Bosco et al., 2016). Due to the growth capability in contaminated and infertile soils  
76 and the potential of heavy metals bioaccumulation (Cristaldi et al., 2020), *A. donax* has been  
77 promising for phytoextraction of contaminants from soil such as Hg (Sagehashi et al., 2011;  
78 Corno et al., 2014), Cd (Yang et al., 2012; Sabeen et al., 2013; Cristaldi et al., 2020), Cr

79 (Kausar et al., 2012), As (Yang et al., 2012), Pb (Guo and Miao, 2010; Yang et al., 2012), Ni  
80 (Papazoglou et al., 2007; Atma et al., 2017), Mn, Zn and Fe (Corno et al., 2014a). The  
81 spontaneous natural growth of *A. donax* in the saline dredged sediments witnessed in the  
82 south of France (Fig. S1) was apparent evidence of the capability of *A. donax* to adapt to  
83 chloride-rich and polluted sediment as a medium for growth. However, the feasibility of  
84 chloride phytoremediation of dredged sediment by *A. donax* as well as its bioaccumulation  
85 capacity is little known to be nominated as a chloride phytoremediation plant (Calheiros et al.,  
86 2012; Jesus et al., 2017; Andreu-Rodríguez et al., 2017). Recently, a laboratory-based  
87 experiment has been implemented to address the growth feasibility of *A. donax* in marine  
88 dredged sediment and to quantify the bioaccumulation rate of chloride in the leaves and  
89 steams of *A. donax* (Sordes et al., 2021). In this study, beyond feasibility, the sustainability of  
90 chloride phytoremediation of sediment by *A. donax*, alone and combined with biomass  
91 valorization was aimed to be assessed in terms of economy and environment through a  
92 comparative life cycle assessment (LCA). The LCA has been applied in some studies as a  
93 common approach to assessing the environmental impacts of phytoremediation (Nie et al.,  
94 2010; Suer and Andersson-Sköld, 2011; Witters et al., 2012; Vigil et al., 2015; Mattei et al.,  
95 2018; O'Connor et al., 2019). However, LCA of phytoremediation of chloride-rich sediment,  
96 as a common pollutant in all marine dredged sediments is still lacking. The economic and  
97 environmental assessments of phytoremediation as well as biomass to bioenergy valorization  
98 chain, combined with laboratory-based phytoremediation trials, offer a holistic approach to  
99 study the feasibility, sustainability, the performance of sediment phytoremediation.

100 This study presents a part of a comprehensive ongoing project for the port of Camargue in the  
101 region of Occitanie in the south of France to provide insight into the feasible and sustainable  
102 remediation and valorization strategies for marine dredged sediment. As a prerequisite for  
103 economic and environmental assessments, a mathematical model was developed to estimate

104 the time interval for phytoremediation of multiple pollutants as well as the yield of biomass to  
105 bioenergy valorization chain including the estimation of biomass yield, bioenergy yield from  
106 valorization schemes and green electricity yield per m<sup>3</sup> of sediment. The mathematical model  
107 was applied to develop life cycle inventories (LCIs) for the chloride phytoremediation of  
108 marine dredged sediment. The objective of this study was to integrate the economic and  
109 environmental LCAs into the laboratory trials to offer a comprehensive insight into the  
110 environmental sustainability, economic viability, and technical feasibility of sediment  
111 phytoremediation by *A. donax*. separately or combined with biomass valorization. This  
112 integrated approach could be customized for other plant species, pollution types, as well as  
113 biomass valorization scenarios.

114

115

## 116 **2. Material and method**

117

### 118 **2.1 Biomass valorization to bioenergy**

119

120 To fulfil the requirements of developing life cycle inventories for harmonized economic and  
121 environmental life cycle assessments, adapted to the functional unit of 1m<sup>3</sup> sediment  
122 phytoremediation, a mathematical model was developed to estimate biomass yield, bioenergy  
123 yield, green electricity generation as well as estimation of phytoremediation time frame  
124 (equation of 1 to 8).

125

#### 126 **2.1.1 Biomass yield**

127

128 The quantity of dry biomass per one cubic meter of sediment (kg/m<sup>3</sup>) per harvest could be  
129 calculated from equation 1.

130

$$131 \quad dm = \left( \frac{PD*(SR/100)*FB*(1-MP/100)}{H} \right) \quad (1)$$

132

133 In which **dm** is the average yield (kg/m<sup>3</sup>) of dry mass expecting from each m<sup>3</sup> of sediment  
 134 per harvest, **PD** is the density of plant cultivation per m<sup>2</sup>, **SR** is the survival rate (%) of the  
 135 plants, **FB** is the average quantity (kg) of fresh biomass per plant per harvest, **MP** is the  
 136 percentage of the moisture content (%) in fresh biomass, **H** is the depth (m) of sediment (soil).

137

138 The range of plant density of 0.5 to 1 for temperate and 1 to 2 plants per m<sup>2</sup> for warmer  
 139 climates (5000-20000 per hectare) are reported (Ge et al., 2016; Corno et al., 2014). The  
 140 planting depth for *A. donax* is recommended to be between 0.15 m to 0.25 m (Corno et al.,  
 141 2014). The moisture content of fresh biomass of *A. donax* is reported to be between 35 to 52  
 142 percent by weight (Ragaglini et al., 2014; Ge et al., 2016) with an average percentage  
 143 moisture (MP) content of 49.2 percent on a mass basis (Melane et al., 2017). The yield range  
 144 of 15 to 41ton dry mass per hectare for fall harvest and 21 to 49ton dry mass for winter  
 145 harvest is reported (Nassi O. Di Nasso et al., 2011; Ping et al., 2014; Ge et al., 2016).

146 In this study, the biomass yield of 20 tons of dry mass per hectare per year, a surface plant  
 147 density of 1 plant per m<sup>2</sup> and a sediment depth of 0.2 m are adopted based on the literature.  
 148 *A. donax* is highly resistant to salinity and the toxicity symptoms appear only after severe salt  
 149 stress with zero plant mortality (De Stefano et al., 2018). In addition, *A. donax* has the  
 150 capability to cope with a wide range of multiple soil and environmental stresses and fast  
 151 recovery following stress relief (Cocozza et al., 2020). Nevertheless, the survival rate (SR) of  
 152 the plant in the extreme condition of multiple stress is incorporated as a parameter into the  
 153 model with the initial value of 97 percent (Zhang et al., 2021).

154

### 2.1.2 Duration of phytoremediation

The maximum time frame required for remediation of sediment with  $q$  pollutant elements up to expected concentration thresholds could be estimated from equation 2.

$$y = \max_{1 \leq i \leq q} \left\{ \frac{\rho_s * (p_{ec_i} - p_{er_i})}{dm * f * d_r} \right\} \quad (2)$$

In which  $y$  is the maximum years expected for the phytoremediation,  $\rho_s$  is the density ( $\text{kg/m}^3$ ) of sediment (soil),  $p_{ec_i}$  is the current concentration ( $\text{mg/kg}_{\text{sediment}}$ ) of  $i^{\text{th}}$  pollutant element in sediment,  $p_{er_i}$  is the regulatory critical concentration ( $\text{mg/kg}_{\text{sediment}}$ ) of  $i^{\text{th}}$  pollutant element in sediment in  $\text{mg/kg}_{\text{sediment}}$ ,  $dm$  is the average yield ( $\text{kg/m}^3$ ) of dry mass expecting from each  $\text{m}^3$  of sediment per harvest,  $f$  is the frequency of harvest per year,  $d_r$  is the deposition (bioaccumulation) rate ( $\text{mg/kg}_{\text{dry biomass}}$ ) of the  $i^{\text{th}}$  pollutant element in dry biomass of the plant,  $q$  is the number of pollutant elements in the sediment.

The density of sediment ( $\rho_s$ ) in this study is considered to be  $2270 \text{ kg/m}^3$  based on the laboratory sediment characterization. The current concentration of leachable chloride ( $\text{Cl}^-$ ) measured after partial dewatering in geotube was  $16000 \text{ mg per kg sediment}$ . According to French regulations, the concentration threshold of leachable chloride in inert sediment is  $800 \text{ mg/kg}$  (legifrance, 2016; Delattre et al., 2022). The frequency of harvest per year ( $f$ ) is reported to be 1-2 times per year (Lewandowski et al., 2003; Ge et al., 2016), two harvests per year ( $f=2$ ) were adopted in this study.

### 2.1.3 Biomass valorization to bioenergy

The bioconversion industry has been developed in four generations to transform biomass into clean and affordable biofuels or chemicals (Demirbas, 2011). First generation biofuels are synthesized from edible biomass cultivated in arable land with the potential pressure on food



182 security. To mitigate the environmental impacts, the usage of arable land and food crops as  
183 the drawbacks of first-generation biofuels, second-generation biofuels are obtained from non-  
184 edible biomass such as perennial grass which could be cultivated in marginal land, as well as  
185 agricultural waste containing lignin and cellulose known as lignocellulosic biomass. The third  
186 and fourth generation biofuels are produced from algae (Sikarwar et al., 2017).

187 To compete with fossil fuels in terms of economy, low cost non-edible lignocellulosic  
188 biomass is a pre-requisite for biofuel production at a commercial scale. Perennial energy  
189 crops could have advantages over annual crops in terms of output to input efficiency of  
190 energy and cost thanks to the allocation of overhead expenses over plant exploitation  
191 (cultivation) lifetime (Angelini et al., 2005). Perennial grasses can easily sprout again after  
192 aerial part harvesting even when they are exposed to toxic trace elements, with no need for  
193 replanting (Rabêlo et al., 2021). Among perennial energy crops producing lignocellulosic  
194 biomass, adapted to the Mediterranean environment, the non-food energy crop of *A. donax*  
195 could be utilized as a second-generation energy feedstock for bioenergy production including  
196 biogas, bioethanol, combustible solid as well as the raw material for green chemistry industry  
197 (Corno, 2016).

198 The potential energy theoretically obtained from the biomass harvested from  
199 phytoremediation of 1m<sup>3</sup> of sediment could be calculated from equation 3.

$$200 \quad \quad \quad \mathbf{BE} = \mathbf{dm} * \mathbf{HCV} * \mathbf{f} \quad \quad \quad (3)$$

201  
202  
203 In which **BE** is the average of potential bioenergy from phytoremediation of one m<sup>3</sup> of  
204 sediment per year, **dm** is the average yield (kg/m<sup>3</sup>) of dry mass expecting from each m<sup>3</sup> of  
205 sediment per harvest, **HCV** is the heat calorific mean value (kJ/kg dry biomass), and **f** is the  
206 frequency of harvest per year.

207 The heat calorific mean value of *A. donax* is reported around 16.8 MJ per kg dry weight  
208 (Krička et al., 2017).

209

#### 210 **2.1.4 Bioenergy yield estimation (Biogas, biomethane, bioethanol and solid** 211 **combustible yield)**

212 Biomass, as the only renewable resource of carbon, can be transformed into solid, liquid, and  
213 gaseous fuels as alternative energy sources to fossil fuels, through thermochemical and  
214 biochemical pathways (Saikia et al., 2015). The bioenergy yield in the forms of gas, liquid,  
215 and solid biofuels from the biomass of *A. donax*, could be obtained from equations 4, 5, 6 and  
216 7.

$$217 \text{ *Solid combustible yield (kg) = DM* } \quad (4)$$

$$218 \text{ *Bioethanol yield (liter) = DM * BETY* } \quad (5)$$

$$219 \text{ *Biomethane yield (Nm<sup>3</sup>) = VS * BMY* } \quad (6)$$

$$220 \text{ *Biogas yield (Nm<sup>3</sup>) = VS * BGY* } \quad (7)$$

221

222 In which DM is dry biomass (kg) of *A. donax*, BETY is bioethanol yield (litre) per kg dry  
223 biomass, VS is volatile solid (kg) of biomass, BMY is biomethane yield (Nm<sup>3</sup>) per kg volatile  
224 solid of *A. donax*, and BGY is biogas yield (Nm<sup>3</sup>) per kg volatile solid of *A. donax*.

225 Having approximately the same heat energy value as wood (18 MJ/kg), *A. donax* has a great  
226 potential for direct burning as a combustible solid fuel.

227 The specific biomethane yield (BMY) of 0.185 normal cubic meters (Nm<sup>3</sup>) (Corno, 2016), the  
228 BMY range of 0.151 - 0.391 Nm<sup>3</sup> (Corno et al., 2014; Dragoni et al., 2015; Ge et al., 2016)  
229 and the highest biochemical methane potential of 0.392 Nm<sup>3</sup> (Ragaglini et al., 2014) per kg of  
230 volatile solids, are reported from the anaerobic digestion of *A. donax* biomass. The volatile  
231 solids (VS) of biomass could be determined from total solid (TS) biomass obtained from  
232 thermal treatment of biomass at 105°C at a constant weight, minus ashes obtained from

233 thermal treatment at 550°C for 10 hours (Ceotto et al., 2021). Biogas yield (BGY) of 0.272  
234 Nm<sup>3</sup> and biomethane yield (BMY) of 0.174 Nm<sup>3</sup> per kg of total solids (TS) are reported from  
235 anaerobic digestion of *A. donax* biomass (Corno et al., 2015). An estimation of approximately  
236 0.075 liters or 0.06 kg of bioethanol yield per kg dry biomass (BETY) of *A. donax* is  
237 presented by Silva et al. 2015 (Lemons e Silva et al., 2015).

238

### 239 **2.1.5 Green electricity yield estimation**

240

241 The quantity of renewable electricity from valorization bioenergy schemes, based on kilowatt  
242 hour (kWh), could be obtained from equation 8:

243

$$244 \text{ *Green electricity yield (kWh) = HCV * BEY * PPE/100 * 1/3600* } \quad (8)$$

245

246 In which **HCV** is heat calorific mean value on kJ/kg for combustible solid, kJ/l for bioethanol,  
247 kJ/Nm<sup>3</sup> for biomethane and biogas, **BEY** is bioenergy yield in forms of solid (kg), liquid (l)  
248 or gas (Nm<sup>3</sup>), **PPE** is efficiency of bioenergy power plant in percentage (%). Since every  
249 hour is 3600 seconds, the quantity is divided into 3600 to convert kJ to kWh.

250 The efficiencies of power plants are diverse depending on the source of fuel and generator  
251 technology. In this study, the cogeneration of heat and power (CHP) plants was adopted to  
252 convert biogas to green electricity. CHP systems typically have total efficiencies between 65  
253 to 80 percent and could be approaching 90 percent (European Commission energy). The  
254 bioenergy power plant in this study is considered to be a CHP power plant with the efficiency  
255 of 50 percent (Payet and Ribak, 2008).

256

### 257 **2.2 Phytoremediation by *A. donax***

258

### 259           **2.2.1 *Arundo donax***

260 *A. donax* or giant reed (giant cane) is a perennial grass with an outstanding growth rate and  
261 biomass yield and low requirements in terms of fertilizer, pesticide, irrigation and soil tillage,  
262 along with environmental plasticity to adapt to wide ranges of pH, salinity, drought and  
263 extreme growing conditions (Krička et al., 2017; Ceotto et al., 2021). In spite of having the  
264 C3 photosynthetic pathway, *A. donax* exhibits an unusual high photosynthetic  
265 CO<sub>2</sub> sequestration rate and biomass production, higher than other C3 grasses and similar to  
266 C4 species (Sidella, 2013). Its growth rate reaches up to 7 cm per day in summer in  
267 Mediterranean environments (Bassam, 2010). Under natural wild conditions, *A. donax* would  
268 yield around 29 t/ha of dry biomass (Angelini et al., 2009; Bassam, 2010) which could reach  
269 up to 55 t/ha or the highest-ever yield of 125 t/ha (Idris et al., 2012) under cropping conditions  
270 (Ververis et al., 2004; Nassi o Di Nasso et al., 2010; Ceotto et al., 2021).

271 The industrial applications of the lignocellulosic biomass of *A. donax* as a feedstock for  
272 second-generation biorefineries such as biomethane, bioethanol and combustible solid (Zhang  
273 et al., 2021; Krička et al., 2017), as well as cellulose production for pulp, paper and  
274 biopolymer industry (Jámbor and Török, 2019; ), has been proven. The cell wall polymers of  
275 lignin, cellulose and hemicellulose are the main three constituents of the complex matrix of  
276 lignocellulose biomass. The higher the lignin content, the more preferable for direct  
277 combustion, while the higher the rest means more suitable for gas and liquid fuel production  
278 (Krička et al., 2017).

279 Due to the high carbon and hydrogen contents, as the basic elements of any fuel, and the high  
280 carbon to nitrogen ratio, as well as the holocellulose to lignin ratio *A. donax* has been  
281 addressed as one of the best species for biogas production (Sánchez et al., 2021) comparable  
282 to conventional annual crops like maize (corn) (Giertl et al., 2022; Corno et al., 2014) and  
283 bioethanol production (Jámbor and Török, 2019). Moreover, the high calorific mean value of

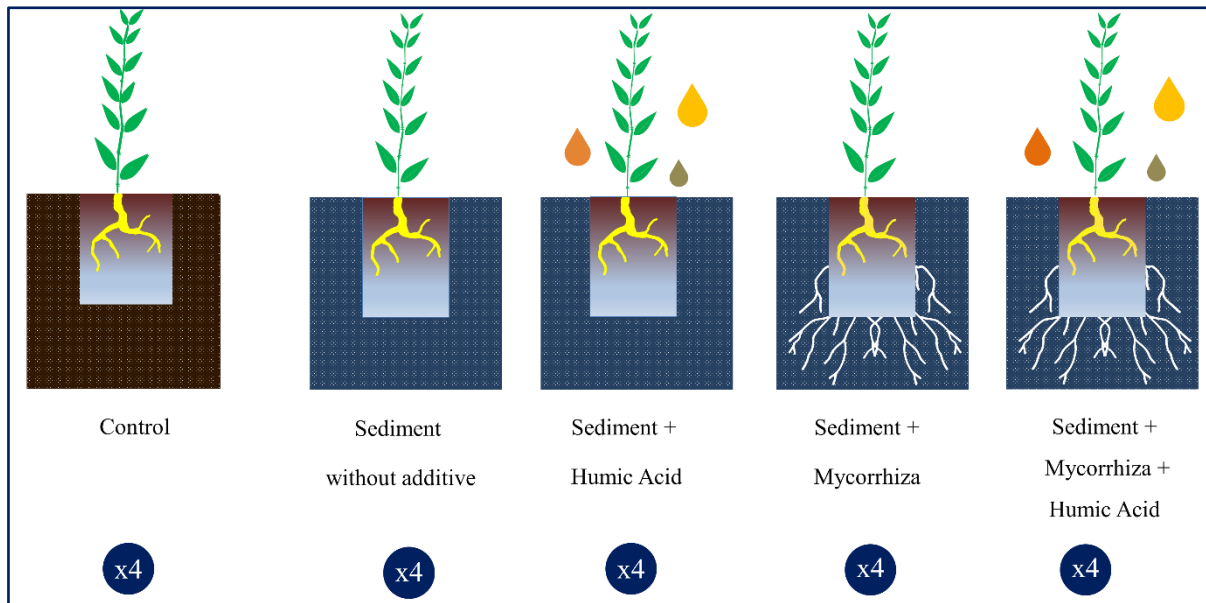
284 the biomass, independent of the growth condition (Angelini et al., 2005) promises the  
285 potential of *A. donax* for direct combustion. The plant versatility, the diverse bio-refinery  
286 products, and the high yield of biomass as a carbon-neutral energy source contributing to the  
287 climate-neutrality (Verónica et al., 2022), nominated *A. donax* among the eligible candidates  
288 to be integrated into phytoremediation.

### 289 **2.2.2 Experimental phytoremediation of marine dredged sediments by *A. donax***

290  
291 To study the capability of *A. donax* in the in-situ chloride phytoremediation of marine dredged  
292 sediment, laboratory-based pot cultivation of *A. donax* was performed. The objective was to  
293 investigate the chloride bioaccumulation performance of *A. donax* in natural conditions and  
294 chemically assisted cropping conditions via adding mycorrhiza to the sediment as well as  
295 humic acid as an alternative to synthetic chelators. Due to not propagating by seeds, two  
296 asexual reproduction types of rooting at the nodes and the cane fragment were applied for the  
297 vegetative reproduction of *A. donax* (Salazar-Zeledón et al., 2015). The reproduction process  
298 was performed within a nursery, accompanied by the partner company of Nymphéa  
299 Distribution (nymphedistrib.com). After 2 months of growing in peat in 3L pots, *A. donax*  
300 plants were acclimatized for two weeks in the greenhouse and were bathed before being  
301 transplanted into the 5 litres of dredged sediments. Dewatered dredged marine sediment from  
302 an ongoing pilot project in port Camargue was used as peat-free cultivation media for in-situ  
303 phytoremediation using *A. donax*.

312 The sediments dredged from port Camargue (Fig. S2) were sampled after dewatering in a  
313 geotube with the chloride concentration of 1.6% of the chemical composition and 33% water  
314 content. Crystalline powder of Humic acid (CAS: 1415-93-6. EINECS: 215-8096) from the  
315 company Alfa Aesar (alfa.com/fr/catalog/041747/) and Mycorrhiza (MYCOR®) from the  
316 company IfTech (iftech.fr/mycor-en-pot-de-23-l-c2x1779336) were supplied. *A. donax* plants

317 were introduced into 4 cultivation media distinguished by 1) sediment without any additive,  
318 2) sediment with the addition of mycorrhiza, 3) sediment with the addition of humic acid, and  
319 4) sediment with the addition of mycorrhiza and humic acid (Sordes et al., 2021). A plant  
320 repotted in the same supplier's peat mixture without any sediment was set up as a control. Pots  
321 were set up in quadruplicate as illustrated in Fig. 1.



322  
323 Fig. 1. Schematic view of *A. donax* cultivation in quadruplicate pots with distinct culture medium  
324 (Sordes et al. 2021)

325 At the end of the experiments, the *A. donax* plants were photographed, the aerial parts  
326 harvested, and treated for further chloride extraction and ion chromatography according to the  
327 protocol of McSorley 2016.

328  
329 **2.3 Environmental assessment**

330 **2.3.1 Life cycle assessment**

331  
332 Life cycle assessment (LCA) is the most popular and recognized analytical framework for  
333 comprehensively assessing the environmental impacts and to identify the hotspots associated  
334 with the entire life cycle of a product or process (Guinee, 2002; Soleimani et al., 2023). The  
335 comparative attributional life cycle assessment was carried out according to ISO 14040, 2006

336 and ISO 14044, 2006 in four standard stages of goal and scope definition, inventory analysis,  
337 impact assessment and interpretation. The life cycle inventories (LCIs) of the  
338 phytoremediation scenarios were developed in openLCA v. 1.11.0, based on laboratory and  
339 field data, the literature and by taking advantage of the inventories from the database  
340 ecoinvent v.3.5 with allocation at the point of substitution (APOS). The ReCiPe midpoint (H),  
341 a state-of-the-art method for life cycle multi-impact assessment harmonized at the midpoint  
342 and endpoint level (Huijbregts et al., 2017) was applied to assess environmental impacts  
343 comprises 18 categories at the midpoint level. At the endpoint level, the midpoint impacts are  
344 accumulated in three main damage categories of human health, resource, and ecosystem  
345 diversity. The environmental impacts of phytoremediation were applied for the normalization  
346 to convert the impact categories with different units into a unitless score by dividing each  
347 impact value to its corresponding of phytoremediation. In addition, the impacts of 1m<sup>3</sup> of  
348 sediment landfill in France were normalized to the corresponding impacts of both  
349 phytoremediation scenarios. The average of normalized impacts is adopted as the single score  
350 environmental impact and illustrated in a graph to provide comparative insight into the  
351 difference in the order of magnitude between the impacts of the landfill and phytoremediation  
352 scenarios.

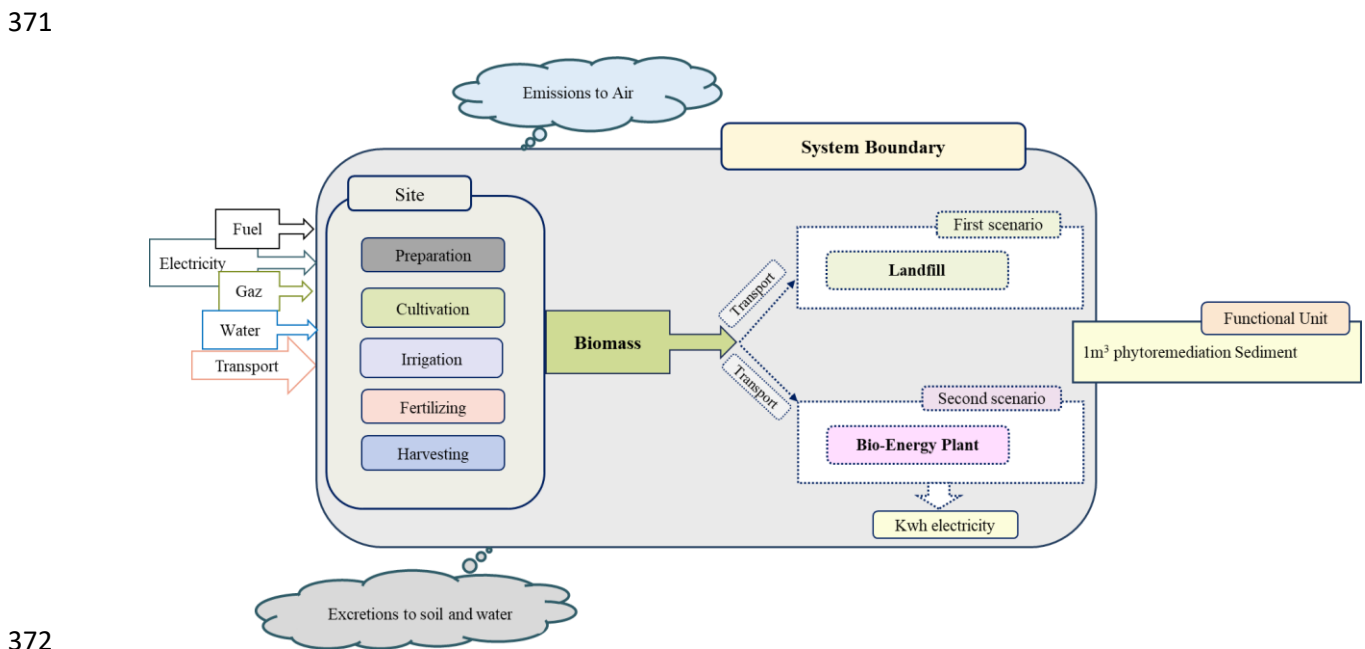
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### 354 **2.3.2 Goal and functional unit of the LCA**

355

356 Goal and scope definitions give a descriptive big picture of the production system in terms of  
357 system boundary and functional unit. A functional unit quantifies the performance of a  
358 product system as a reference unit to ensure comparable LCA studies and reliable results.  
359 Accordingly, in-situ treatment of one cubic meter (1m<sup>3</sup>) of sediment was adopted as the  
360 functional unit in this study. All the flows coming into the system boundary such as energy,  
361 transport, water and raw materials and outgoing flows including emissions to air, soil and

362 water were considered. All the processes in the phytoremediation and biomass valorization  
 363 scenarios were considered in the cradle-to-gate system boundary illustrated in Fig.1. The  
 364 system boundary does not include the laboratory-based growing of plants and the associated  
 365 trials. As a cut-off approach, the sediment was considered to be a recyclable material with  
 366 zero environmental impacts, allocating all the environmental impacts up to the end of  
 367 sediment dewatering in the geotube on land, to the dredging operation. To provide more  
 368 insight into the sensitive parameters, the results of sensitivity analysis and uncertainty analysis  
 369 are presented in this study. For the reliability of the comparative assessments between  
 370 scenarios, consistency was sustained in all parameters and inventories.



372  
 373 Fig. 2. Scheme of the system boundary, which includes the site preparation, production of  
 374 plants, planting, watering, fertilizing, harvesting, input raw materials, bioenergy power plant,  
 375 transport of materials to the power plant, and the green electricity production in the power  
 376 plant.

377  
 378 Among the biomass to bioenergy valorization schemes the biogas production from biomass  
 379 was adopted as a biomass valorization approach in this study. To incorporate the impacts of



380 biomass transformation to biogas and ultimate green electricity, it was assumed that the same  
381 quantity of electricity produced with the fossil fuel of natural gas in the same power plant is  
382 avoided. In this way, the economic and environmental benefits of integrating biomass  
383 valorization into phytoremediation arises from the replacing of fossil fuel (natural gas) with  
384 synthetic biogas for green electricity production in power plant.

385

### 386 **2.3.3 Data (biomass characterization and bioenergy production)**

387

388 The physicochemical and geotechnical specifications of the sediment samples of the port  
389 Camargue were characterized by the CISMA environment laboratory in France (Table S1).  
390 The analysis confirmed that sediments are non-hazardous but not inert in terms of some  
391 pollution elements including chloride. The mean values of the materials and energy flows and  
392 the processes within the system boundary were adopted from the project internal data,  
393 laboratory analysis as well as background data. The transport of raw materials and harvested  
394 biomass were estimated from the origin to the destination using Google Maps.

395 The agricultural activities such as soil preparation, cultivation, fertilization, harvesting,  
396 machine operations and transport to the anaerobic digester biogas power plant of EveRé  
397 (evere.fr), 97.5 km from the port of Camargue are included in the assessment. The chloride-  
398 rich biomass is transformed into synthetic biogas through an anaerobic digestion plant and the  
399 biogas was assumed to be burnt in a combined heat and power (CHP) plant also known as  
400 cogeneration to produce electricity. In the scenario of phytoremediation, it is assumed that the  
401 harvested biomass would be landfilled in a site (Bellegarde) with 53 km distance from the  
402 port of Camargue. The volume quantity of biogas per kg dry mass of *A. donax* was estimated  
403 based on 0.272 Nm<sup>3</sup> biogas per kg total solid (Corno, 2016). The annual biomass yield was  
404 assumed to be 20 tons of dry mass per hectare from two harvests per year.

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## 2.4 Uncertainty Analysis

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The uncertainty in the parameters may result in overestimation or underestimation of the environmental impacts. A Monte Carlo (MC) simulation is a tool to obtain the probability distribution for each environmental impact category due to the combined uncertainties of the model parameters. Random sampling from the probability distribution functions of the incorporated parameters in the model, MC could comprehensively assess the sensitivity of the environmental impact categories to the uncertainties in the life cycle inventories (Soleimani et al., 2023). Monte Carlo simulations in openLCA unveiled the confidence interval in each impact category. The 90% confidence interval (5% percentile to 95% percentile) of the endpoint environmental impact values, resulting from 1000 MC simulations have been illustrated as the upper and lower error bars in the graph of environmental impacts.

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## 2.5 Developing parametric life cycle inventories (LCI) for environmental sensitivity analysis

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Sensitivity analysis determines how big the outcomes of a model are sensitive to the variations of the input parameters and unveils the relative importance of the input parameters. As a prerequisite for sensitivity analysis, a parametric model is needed to be developed through incorporating the input parameters in the model (Table S2), mathematically linked together and to the outputs (Soleimani and Gilbert, 2020). Based on Eq.1, Eq.3 and Eq.4, experimental data from the lab and the literature, the parametric LCIs were developed in openLCA for 'one-at-a-time (OAT)' sensitivity analysis of the environmental impacts. In the OAT sensitivity analysis, the relative change in the environmental impacts due to  $\pm 10\%$  relative change in the target parameter while all other parameters held constant, were calculated. To develop the life cycle inventory of the phytoremediation processes and

433 valorization scenario, all the materials consumed, and the process carried out including the  
434 preparation of the site, plant cultivation and harvesting until the end of the valorization of the  
435 biomass, were included.

436

## 437 **2.6 Cost and revenue evaluation**

438

439 A complementary economic evaluation parallel to the environmental assessment of  
440 phytoremediation alone and combined with the biomass valorization chain, provides insight  
441 into the viability of scenarios for decision-makers. Accordingly, the Cost Revenue Analysis  
442 was conducted in Excel based on the aforementioned equations of 1 to 8, information in the  
443 literature as well as the market prices in France. The average cost of €1200/ha (Jámbor and  
444 Török, 2019), and €700/ha (Pilu et al., 2013), for the cultivation of *A. donax* on an annually  
445 basis are reported in the literature for a 15 to 20-year life span. The cost of electricity  
446 generation with the gas turbine in combined heat and power (CHP) systems is estimated to be  
447 0.1436 \$/kWh, and the cost of heat generation is estimated to be 0.0738 \$/kWh (Kang and  
448 Cao, 2014; Abanades et al., 2022). A range of 0.05\$/kWh to 0.18\$/kWh was reported for  
449 electricity generation in gas turbines based on the volume fraction of methane in biogas, the  
450 size of powerplant and the price of biogas (Barzegaravval et al., 2018).

451 The cost of 1m<sup>3</sup> sediment phytoremediation per year was calculated based on assuming 5000  
452 euros cost for one hectare of *A. donax* per year and the cost of 1 kWh renewable electricity  
453 from biogas in a CHP was assumed to be 0.13 €/kWh. The revenue per kWh electricity of  
454 0.18 €/kWh, adopted from an average price of French electricity suppliers in 2023 considered  
455 as a negative cost.

456

## 457 **3 Results**

458 In this study, a laboratory-based experiment was integrated into economic and environmental  
459 life cycle assessment to offer a holistic approach to assess the impacts of phytoremediation  
460 combined with biomass valorization. A series of experiments were set up to study the  
461 feasibility of chloride phytoremediation by *A. donax* as well as its chloride bioaccumulation  
462 performance. The results of economic and environmental assessments and the laboratory trials  
463 are reported.

464

### 465 **3.1 Experimental assessment of chloride phytoremediation performance of** 466 ***A. donax***

467

468 The feasibility of phytoremediation of contaminated chloride-rich sediment by *A. donax* and  
469 its bioaccumulation performance was assessed through cultivation, growing and treatment  
470 trials. The deposition rates of chloride in aerial parts of *A. donax* in sediment treated  
471 separately with humic acid (8921mg/kg) and mycorrhiza (8221 mg/kg) were obtained lower  
472 than the deposition rate in non-treated sediment (9940 mg/kg). However, the sediment treated  
473 with combined humic acid and mycorrhiza resulted in more than a 50% increase in chloride  
474 deposition rate (15192 mg/kg) in aerial parts of *A. donax*. The reasons of the inhibitory and  
475 excitatory roles of separate and combined humic acid and mycorrhiza are not in the scope of  
476 this study. The mean deposition rate of chloride in aerial parts of *A. donax* cultivated in non-  
477 treated sediment, 9940 mg/kg dry biomass, was retained for the estimation of the required  
478 time frame of phytoremediation (Fig. 3).

479

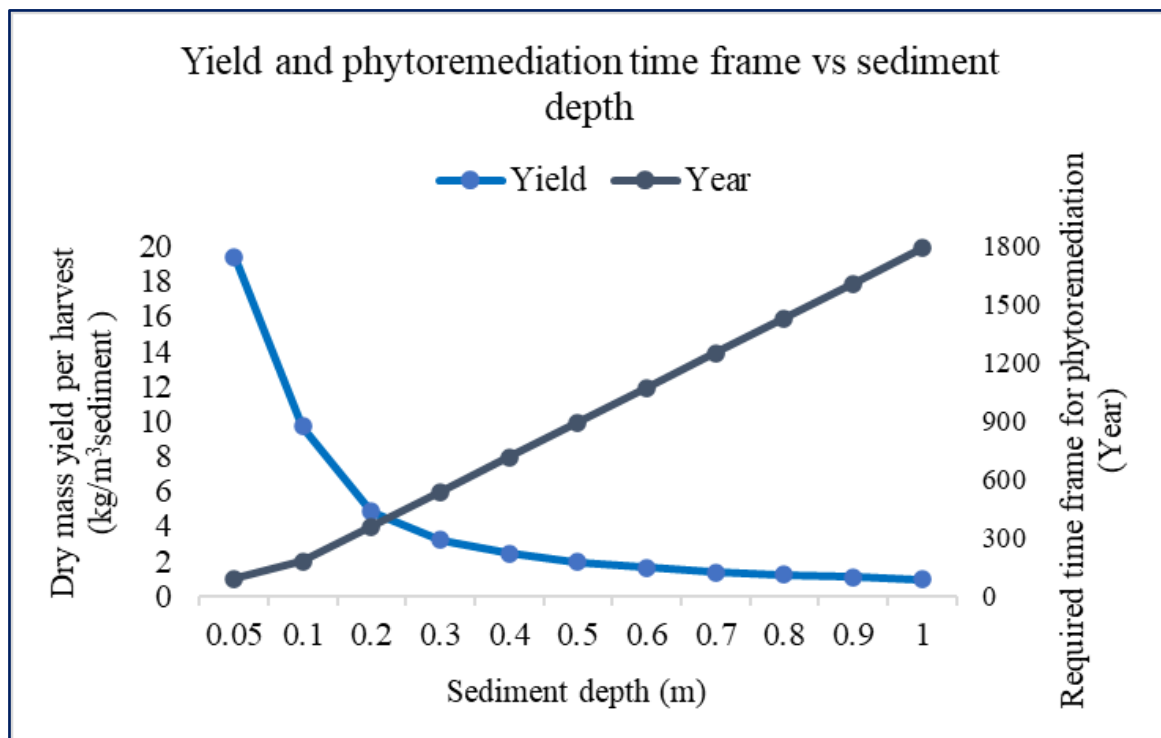
### 480 **3.2 Biomass yield and duration of phytoremediation versus sediment depth**

481

482 Since the significant part of the root system of perennial grasses is mostly developed in the 0-  
483 15 cm upper surface of the soil (Gist and Smith, 1948; Rabêlo et al., 2021), the sediment  
484 depth (H) is very important in the performance of grass-based phytoremediation. On the other

485 side, according to equations 1 and 2, the sediment depth (H) is a key parameter to determine  
 486 the plant density in a volume of sediment (plant/m<sup>3</sup>), the estimation of the time frame of  
 487 phytoremediation and the dry biomass yield per m<sup>3</sup> of sediment. The variation in the  
 488 phytoremediation time interval and the dry biomass yield of *A. donax* versus the variations in  
 489 the sediment depth (H), based on equations 1 and 2, are visualized in Fig. 3.

490



491

492 Fig. 3. Visualized linear relationship between the sediment depth and time frame of chloride  
 493 phytoremediation (year) and inverse relationship between the sediment depth and biomass  
 494 yield (kg/m<sup>3</sup>sediment)

495

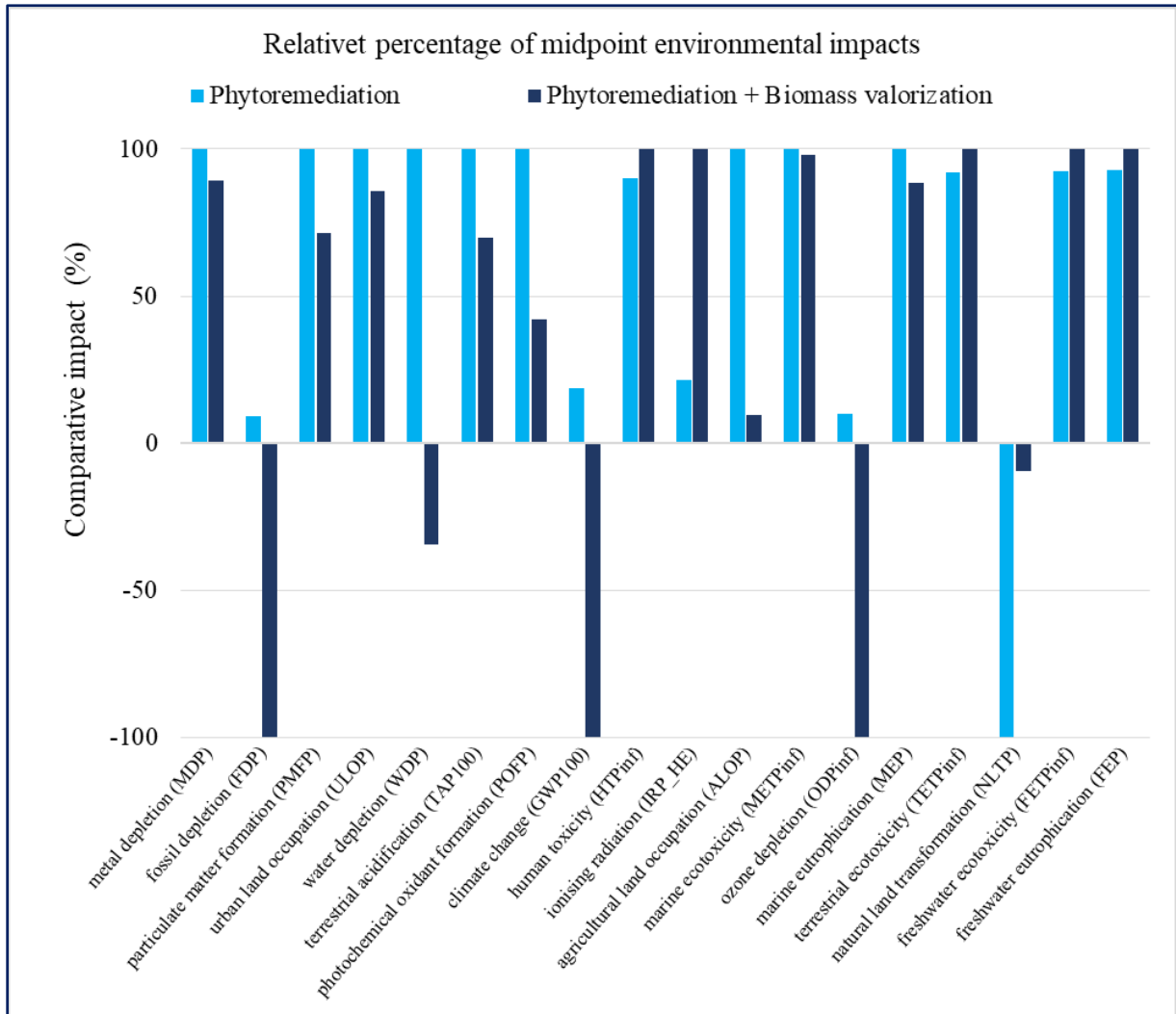
496 Assuming 20 cm sediment depth, the graph in Fig. 3 reveals that lowering the sediment  
 497 chloride level from the current concentration of 16000 mg/kg up to the target regulatory  
 498 concentration of 800 mg/kg, would not be achievable in less than 357 years.

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### 3.3 Comparative environmental impacts of phytoremediation scenarios

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The impacts of phytoremediation of 1m<sup>3</sup> sediment, alone and integrated into green electricity generation in a CHP power plant, are compared in 18 impact categories of ReCiPe midpoint in Fig. 4, on a relative percentage basis.

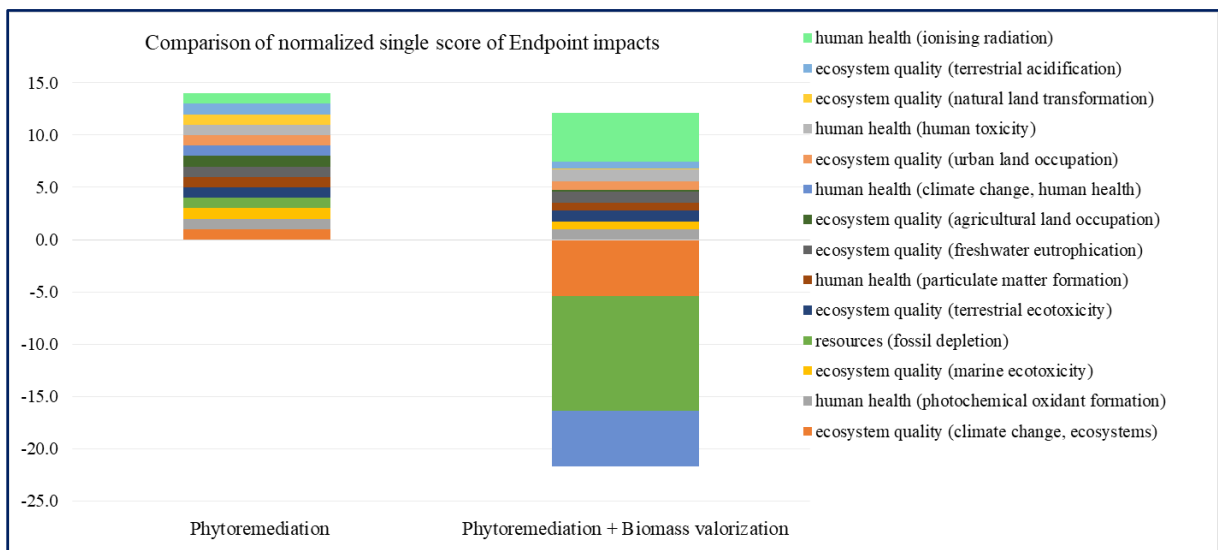


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Fig. 4. Comparative environmental impacts of phytoremediation of 1m<sup>3</sup> sediment, alone and integrated with biomass valorization to renewable electricity, in 18 impact categories of ReCiPe midpoint (H), based on relative percentage.

It is apparent that the phytoremediation scenarios could be distinguished by negative quantities for midpoint impacts of fossil depletion, water depletion, climate change and ozone

512 depletion. To have an idea about the final impacts on ecosystem quality, resources and human  
 513 health, the endpoint impacts of phytoremediation scenarios were obtained in a dimensionless  
 514 score of point (Pt) from the ReCiPe endpoint method. The endpoint impacts of the scenarios,  
 515 normalized to the corresponding of phytoremediation scenario without biomass valorization,  
 516 are visualized in Fig. 5 to provide comparative insight into the difference between the  
 517 scenarios at the endpoint level.



518  
 519 Fig. 5. Comparative normalized endpoint environmental impacts of sediment  
 520 phytoremediation scenarios obtained from ReCiPe endpoint method.

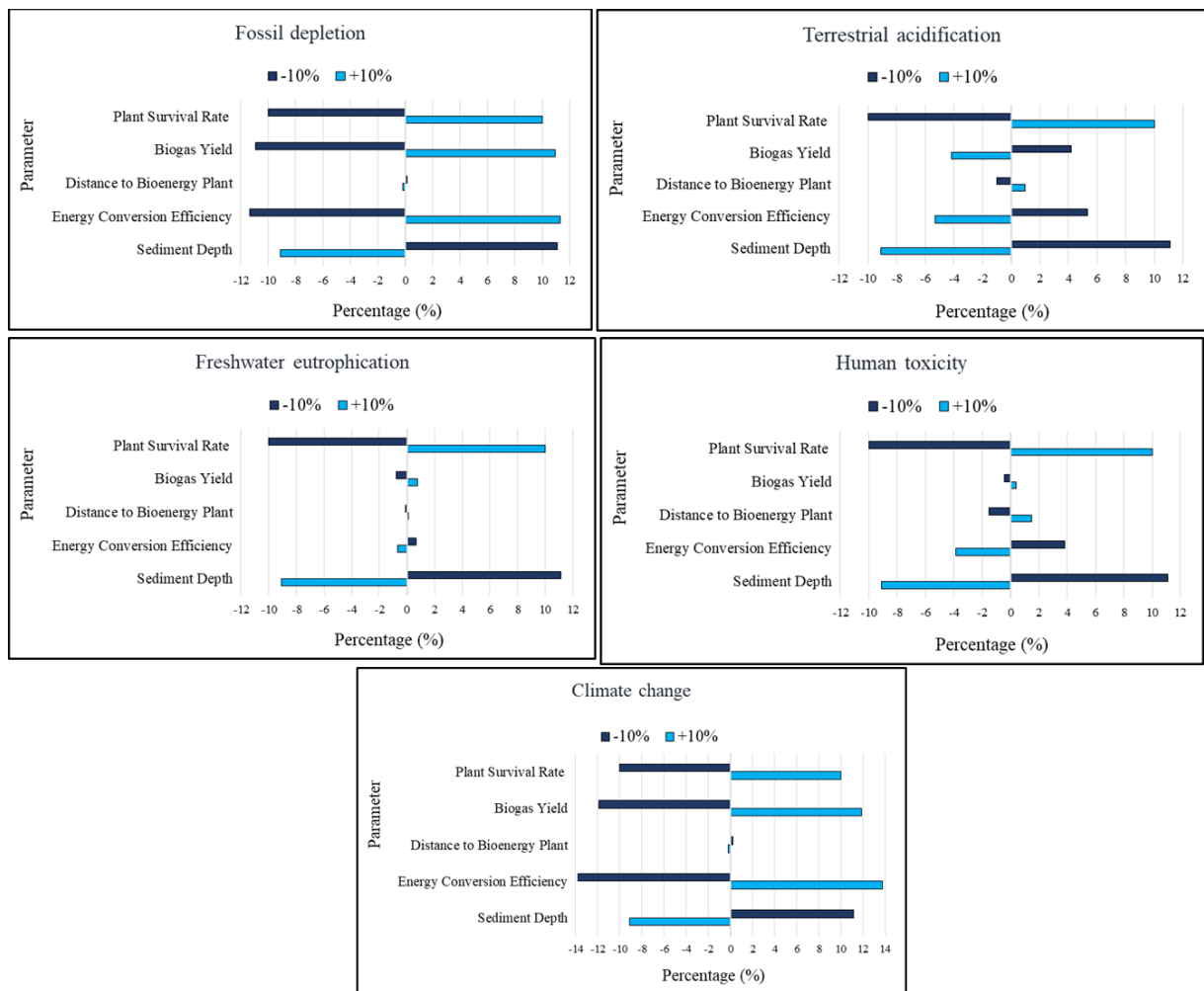
521  
 522 At the endpoint level, the scenarios could be distinguished by negative impacts in categories  
 523 of resources (fossil depletion), ecosystem quality (climate change) and human health (climate  
 524 change).

525  
 526 **3.4 Sensitivity analysis of environmental impacts of 1m<sup>3</sup> sediment**  
 527 **phytoremediation integrated with biomass valorization**

528  
 529 The parametric LCIs enabled to perform the sensitivity analysis on intended parameters, were  
 530 incorporated in the models. The sensitivity of local and global midpoint environmental

531 impacts of climate change, fossil depletion, freshwater eutrophication, human toxicity, and  
 532 terrestrial acidification conducted in openLCA, the results are illustrated in separate graphs in  
 533 Fig. 6. Each graph shows the variation percentage in the environmental impact due to a  $\pm 10\%$   
 534 change of the targeted input parameters of sediment depth, the energy conversion efficiency  
 535 of the bioenergy power plant, distance to the bioenergy power plant, biogas yield and plant  
 536 survival rate.

537



538

539 Fig. 6. Variation percentages in the environmental impacts of phytoremediation of  $1 \text{ m}^3$   
 540 sediment integrated with biomass valorization in midpoint local and global impact categories  
 541 of climate change, fossil depletion, freshwater eutrophication, human toxicity, and terrestrial  
 542 acidification, due to  $\pm 10\%$  one-at-time change of the target input parameters.

543



544 The graphs illustrate that climate change and fossil depletion have the maximum sensitivity to  
545 the efficiency of the power plant and biogas yield as was expected. The impact categories  
546 have the minimum sensitivity to the distance from the site to the bioenergy power plant,  
547 except for human toxicity. Relatively high sensitivity to sediment depth and plant survival  
548 rate is common between all the impact categories.

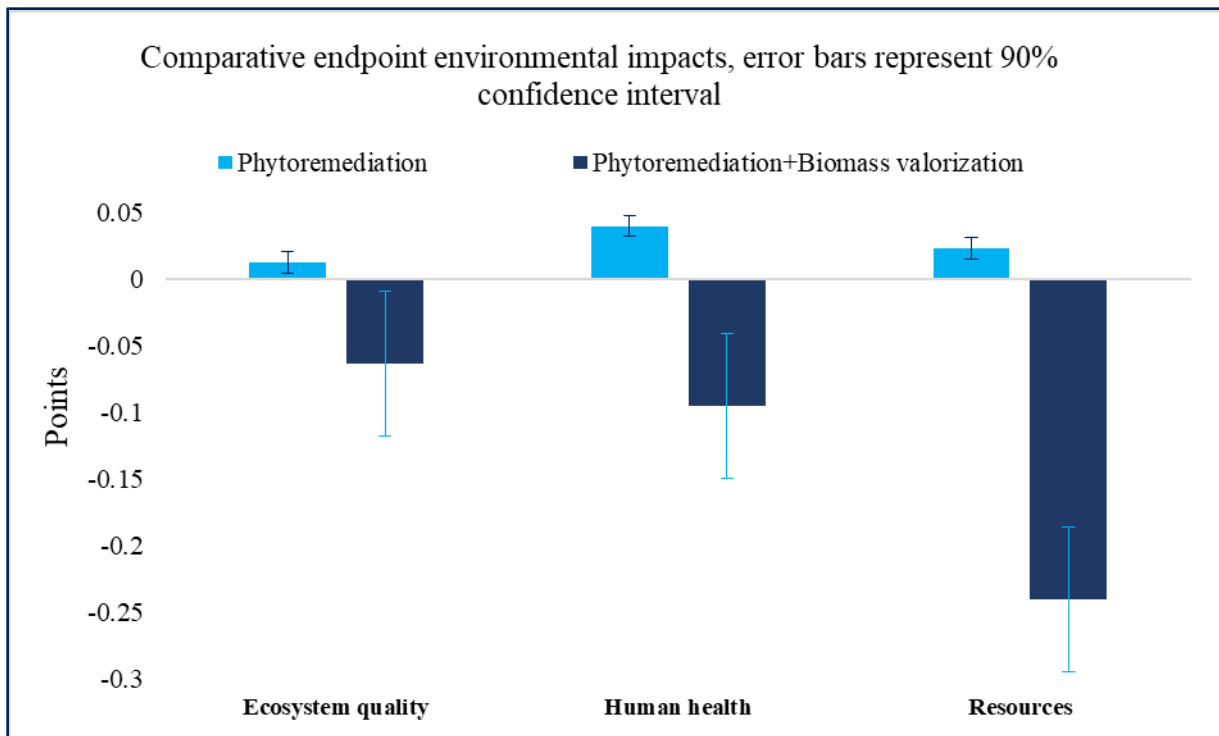
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### 550 **3.5 Uncertainty analysis of environmental impacts of sediment phytoremediation** 551 **scenarios**

552

553 The uncertainty analysis takes into account the uncertainty in all the parameters incorporated  
554 in the model to determine the lower and upper bands in each impact category with 90%  
555 confidence. The Monte Carlo simulation was carried out in openLCA for both  
556 phytoremediation scenarios to unveil the uncertainties in the endpoint impact categories of  
557 Human health, Resources and Ecosystem quality. The uncertainties in the endpoint impacts  
558 obtained from 1000 runs of Monte Carlo simulations are visualized as the error bars in Fig. 7.  
559 The upper band represents the 5% percentile, the lower band represents the 95% percentile  
560 and the range between them represents 90% confidence interval in each impact category.

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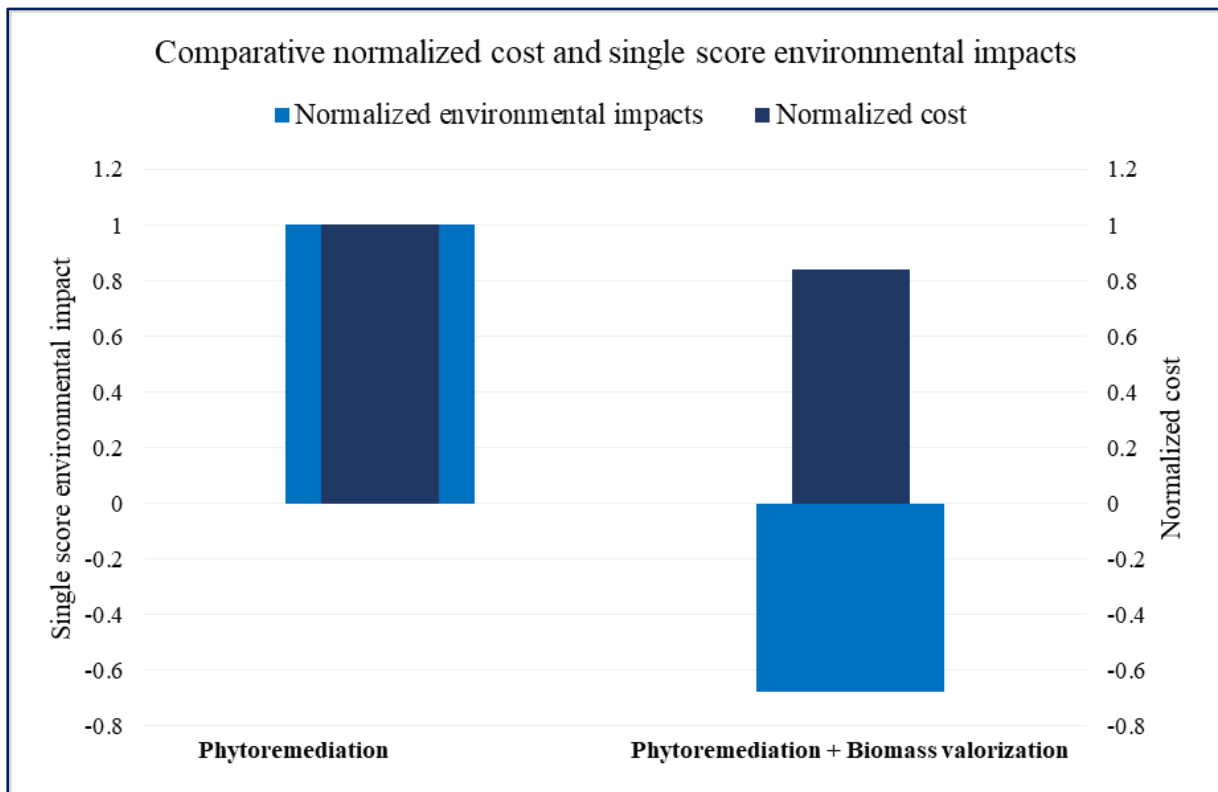


562  
 563 Fig. 7. Comparative endpoint environmental impacts of phytoremediation of 1m<sup>3</sup> sediment,  
 564 alone and combined with biomass valorization, along with the upper and lower error bars  
 565 representing 5% percentile and 95% percentile and the interval of 90% confidence in each  
 566 impact category.

### 567 **3.6 Comparative economic and environmental impacts assessment of sediment** 568 **phytoremediation scenarios**

569  
 570 To provide a comparative overall view for the decision-makers on the economic and  
 571 environmental costs of the scenarios, the 18 midpoint environmental impacts, normalized to  
 572 the corresponding of phytoremediation were integrated into a single score. The costs of both  
 573 scenarios were normalized to the corresponding of phytoremediation as well. To compare the  
 574 sustainability of scenarios, the mean values of singles score environmental impacts, and the  
 575 normalized costs are superimposed in a single graph in Fig. 8.

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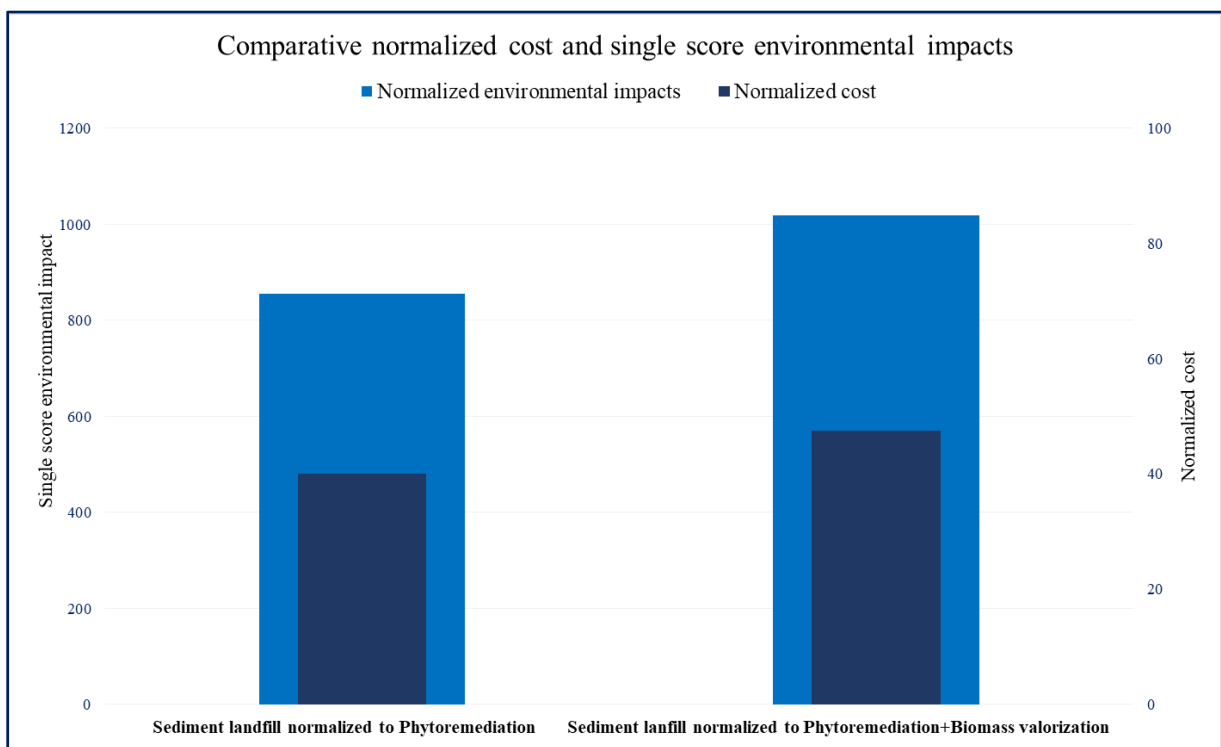
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578 Fig. 8. Singles score environmental impacts and cost of scenarios, normalized to  
 579 corresponding of phytoremediation.

580

581 The graph in Fig. 8 illustrates that the scenario of phytoremediation integrated with biomass  
 582 valorization to bioenergy would have a relatively negative overall environmental impact  
 583 compared to the phytoremediation scenario. From an economic perspective, inferred from the  
 584 graph, biomass valorization could partially compensate for the costs of sediment  
 585 phytoremediation. The rate of cost compensation depends on biomass yield per hectare, the  
 586 market price of bioenergy, and the efficiency of the biomass valorization chain. In order to  
 587 compare the costs and environmental impacts of other sediment management approaches with  
 588 those of phytoremediation, sediment landfill was adopted for elaboration as a conventional  
 589 alternative. The environmental impacts of sediment landfill, based on the sediment  
 590 composition analysis (Table S1), obtained in 18 impact categories from the same method of  
 591 ReCiPe midpoint (H), were normalized separately to those of phytoremediation scenarios.

592 The summation of unitless values were divided to corresponding of phytoremediation  
 593 scenarios to obtain a single score. The cost of a 1m<sup>3</sup> sediment landfill in the French market,  
 594 100 euros was adopted as the cost of a landfill and was normalized separately to  
 595 corresponding of the phytoremediation scenarios. The means of single score impacts as well  
 596 as the normalized cost of sediment landfill in France, are superimposed in a single graph to  
 597 offer insight into the difference in the order of magnitude between the cost and impacts of  
 598 1m<sup>3</sup> sediment landfill and those of annual sediment phytoremediation scenarios.



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 600  
 601 Fig. 9. Environmental impacts and cost of 1m<sup>3</sup> sediment landfill, normalized to corresponding  
 602 phytoremediation scenarios, integrated to singles scores are compared along with the  
 603 normalized costs.

604  
 605 The graph shows that the environmental impacts of sediment landfill could be hundreds of  
 606 times larger than the annual impacts of phytoremediation scenarios, mainly due to the  
 607 leaching and emission of multiple trace elements and inorganic pollutions into air, water, and

608 soil. In terms of economy, the cost of a sediment landfill could be tens of times bigger than  
609 the annual cost of phytoremediation scenarios.

610

611

#### 612 **4 Discussion**

613

614 The concentration of leachable chloride as a common element in all marine dredged  
615 sediments generally exceeds the regulatory threshold value. From the laboratory trials of  
616 growing *A. donax* in non-treated sediment and treated with Humic acid and Mycorrhiza, its  
617 tolerance to multi-element pollutants and chloride-rich sediment was confirmed with zero  
618 mortality rate of cultivated plants. In terms of the chloride bioaccumulation performance, the  
619 experiments unveiled that the accumulation capability of *A. donax* is considerable enough to  
620 be categorized among hyperaccumulator plants, which is generally referred to the plants with  
621 accumulation capability of more than 1000 mg/kg dry mass (Roy et al., 2005). Based on these  
622 results, conducting phytoremediation for chloride-rich sediment via *A. donax* is feasible.  
623 However, the estimated time frame of phytoremediation showed that due to the high  
624 concentration of chloride in sediment compared to the regulatory value to be considered as an  
625 inert material (800 mg/kg), phytoremediation of the sediment dredged from the port of  
626 Camargue is not practical in a reasonable duration of time.

627

628 According to the inverse relationship between phytoremediation time frame and the chloride  
629 deposition rate of *A. donax* ( $d_r$ ), chemically assisted increase in  $d_r$  up to 15192 mg/kg dry  
630 mass by combined application of Humic Acid and Mycorrhiza would decrease the time frame  
631 to 234 year which is not applicable as well. To have the chloride inert sediment in a  
632 reasonable time frame of 20 years, based on the equation 2, the chloride concentration should  
633 be decreased from the current quantity of 16000 mg/kg up to 1650 mg/kg, which might be

634 achievable through complete sediment dewatering in geotube or sediment washing during a  
635 dredging operation on the sea, or any other appropriate pretreatment. Although  
636 phytoremediation, unlike other conventional physicochemical remediation techniques, is  
637 categorized among the green technologies (Nedjimi, 2021), like any other agricultural activity  
638 has environmental impacts as is apparent in the positive values of 17 midpoint impact  
639 categories. Considerable negative midpoint and endpoint environmental impacts emerged  
640 when the valorization of biomass to green electricity was integrated into phytoremediation.

641

642 Because of the importance of considering sediment depth in the effectiveness of plant rooting  
643 system as well as estimating the time frame, the surface area may not be an appropriate  
644 functional unit in the phytoremediation LCA studies. In spite of the recommendations to  
645 consider one hectare as a suitable functional unit for phytoremediation LCAs (Morais and  
646 Delerue-Matos, 2010; Vigil et al., 2015) the more appropriate functional unit seems to be  $1\text{m}^3$   
647 of sediment: 1) to incorporate the sediment depth into the model, 2) to consider the  
648 effectiveness of plant rooting system, 3) to estimate the phytoremediation time frame and 4)  
649 to retain economic and environmental comparability to other valorization or landfill scenarios  
650 usually are expressed on volume or mass basis, and 5) to estimate harvested biomass per  $\text{m}^3$   
651 of sediment based on plant cultivation density.

652

653 A sensitivity analysis was carried out to identify how variations in the input parameters  
654 contribute to the targeted local and global impacts to determine the key parameters in each  
655 impact category. The sensitivity analysis unveiled that the parameters involve in biomass  
656 yields per  $1\text{m}^3$  sediment such as the sediment depth and the survival rate of plants as well as  
657 the parameters involve in ultimate energy yields such as the biogas yield and the efficiency of  
658 the bioenergy power plant are the key parameters affecting the environmental impacts. While

659 sensitivity analysis determines the relative importance of the input parameters in model  
660 outputs, uncertainty analysis unveils the entire possible outcomes together with their level of  
661 certainty represented by the confidence interval. The 90 percent confidence interval means  
662 that considering all uncertainties in the model, the impacts would be in the confidence interval  
663 with the probability of occurrence of 90 percent. According to the results of uncertainty  
664 analysis, the uncertainty in the impacts of phytoremediation integrated with biomass  
665 valorization is higher than the corresponding of phytoremediation, but none of the  
666 uncertainties is large enough to change the game between the scenarios.

667

668 The comparative economic and environmental impacts of sediment phytoremediation  
669 scenarios, demonstrated that biomass valorization could offset the environmental impacts and  
670 partially compensate the costs of phytoremediation, offering a more viable sediment  
671 remediation scenario. The mitigation of the environmental impacts could mainly be attributed  
672 to carbon sequestration and the avoided fossil fuels for electricity generation. Since the values  
673 for biomass yield, bioenergy yield, power plant efficiency, etc., considered in life cycle  
674 assessments are conservatively on an average basis, higher benefits in terms of economy and  
675 environment could be expected from higher biomass yield in cropping conditions and  
676 improvements in the biomass valorization chain. In addition to the improvements and  
677 optimizations, the regular hike in the price of fossil fuels as the main competitor for  
678 renewable bioenergy would offer more desirability for biomass valorization in terms of  
679 economy. The solid digestate remainder of anaerobic digestion which is nutrient-rich and  
680 comparable to manure could be applied to replace chemical fertilizers (Abanades et al., 2022).  
681 As far as the environmental and economic profits of the solid digestate are not considered in  
682 this study, additional benefits would be expected from biomass valorization.

683 The costs and environmental impacts of sediment landfill, as an inevitable alternative scenario  
684 for phytoremediation, compared to corresponding of phytoremediation scenarios,  
685 demonstrates that phytoremediation of  $1\text{m}^3$  sediment would be relatively much higher viable  
686 than the landfill, even without biomass valorization. In comparisons between the landfill and  
687 phytoremediation of sediment, the time frame is compromised because of the long-term  
688 nature of phytoremediation. In case the phytoremediation of non-inert chloride-polluted  
689 sediment is not achievable in a reasonable and realistic time frame, phytoremediation could be  
690 considered as a pretreatment for other sediment valorization scenarios such as substitution in  
691 cementitious materials (Soleimani et al., 2023) or marine grade concrete (Hayek et al., 2023)  
692 after partial remediation of detrimental effects of pollutants.

693

694

## 695 **5 Conclusion**

696

697 A mathematical model was developed to estimate the maximum time frame for  
698 phytoremediation of multiple-pollutant sediment as well as the yield of biomass to bioenergy  
699 valorization chain including the estimation of biomass yield per  $\text{m}^3$  of sediment, the bioenergy  
700 yield from valorization schemes and final green electricity per  $\text{m}^3$  of sediment, as a  
701 prerequisite for economic and environmental assessments. The mathematical model was  
702 applied to develop parametric life cycle inventories for two scenarios of phytoremediation  
703 separately or integrated with biomass valorization. A laboratory-based experiment was  
704 integrated into economic and environmental life cycle assessment to offer a holistic  
705 assessment approach.

706

707 From the comprehensive economic, environmental, and experimental assessments, the  
708 following implications could be inferred:



709

710 • Integrating biomass to bioenergy valorization chain into sediment phytoremediation  
711 would offer superior viability in terms of economy and environment.

712

713 • The sediment depth is very important for the effectiveness of the plant root system in  
714 phytoremediation, as well as the estimation of the time frame and the biomass yield  
715 per m<sup>3</sup> sediment.

716 • Volume of sediment (1m<sup>3</sup>) is a more appropriate functional unit for LCAs of  
717 phytoremediation than the surface area (1ha) in order to incorporate the sediment  
718 depth into the model to consider the plant rooting system and retain economic and  
719 environmental comparability to other valorization scenarios.

720

721 • The phytoremediation of non-inert chloride-polluted sediment at the current state of  
722 the art may not be a short-term strategy achievable in a reasonable and realistic time  
723 frame.

724

725 • The model could be evolved more, through the incorporation of other targeted  
726 influential parameters and their uncertainties to provide comprehensive insight into the  
727 affecting parameters on the economic and environmental impacts.

728

729 • Phytomanagement of dredged sediment could be carbon negative scenario thanks to  
730 carbon sequestration and avoiding fossil fuels.

731

732 • As a recommendation for future work, further economic and environmental  
733 assessments for other biomass valorization schemes integrated into the

734 phytoremediation, could enlighten more the perspective of sediment  
735 phytoremediation.

736  
737 • As potential areas for future investigations, the model developed in this study is a  
738 general model applicable for different types of plants, contaminated sediment and  
739 soils, and biomass to bioenergy valorization schemes.

740

#### 741 **CRedit authorship contribution statement**

742 Not applicable.

743

#### 744 **Data availability**

745 Data will be made available on request.

746

#### 747 **Declaration of competing interest**

748 The authors declare that they have no known competing financial interests or personal  
749 relationships that could have appeared to influence the work reported in this paper.

750

#### 751 **Acknowledgements**

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753 Union, the Occitanie Region, and the Prefecture of the Occitanie Region. We are grateful to  
754 Ad-OCC, the staff of the ports of Camargue and Pérols particularly Yan Roux and Willy  
755 Paramé.

756

757

#### 758 **Appendix A. Supplementary data**

759 Supplementary data to this article can be found online.

760

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