

Viewpoint

Recycling and Reuse of Sediments in Agriculture: Where Is the Problem?

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Abstract: Though suggested by international conventions for a long time, there are still several technical and legislative limitations to a complete reuse and recycling of dredged sediments. In particular, reuse of unpolluted sediments can be practiced, whereas sediment recycling is still affected by several downsides, and a significant proportion of the recycled fine sediments has no practical use and must be landfilled. However, the silty clayey fraction of the recycled sediments is rich in organic matter and macro- and micronutrients useful for plant growth. Nevertheless, sediment recycling in agriculture is not possible, even in non-food agricultural sectors, due to the lack of a permissive legislation and of consolidated supply chains. In addition to plant nutrients, the silty-clay sediment fraction may also accumulate organic and inorganic pollutants, and while the organic pollutants can be effectively biodegraded, metals and metalloids may concentrate at concentrations higher than the limits set by the environmental and agricultural legislations. In this paper, I briefly summarize the scientific evidence on the potential reuse and recycling of sediments in agriculture, and I discuss the main reasons for hindrance of sediment recycling in agriculture. I also present evidence from a real industrial biodegradation process that produces bioremediated fine sediment fractions with suitable properties as a mineral ingredient for plant-growing media. I propose that nutrient-rich recycled sediments could be reconsidered as a component material category in the new EU regulation on fertilizers.



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1. Introduction

Sediment is a natural mineral matrix formed by the weathering and erosion of bedrocks under the action of water and climatic and biotic factors. Sediments are transported by wind, water, or gravity force and deposited by sedimentation even at long distances from their origin. Depending on the particle size, sediments are classified as boulder (>256 mm), cobble (64–256), very coarse gravel (32–64 mm), coarse gravel (16–32 mm), medium gravel (8–16 mm), fine gravel (4–8 mm), very fine gravel (2–4 mm), very coarse sand (1–2 mm), coarse sand (0.5–1 mm), medium sand (0.25–0.5 mm), fine sand (125–250 µm), very fine sand (62.5–125 µm), silt (3.9–62.5 µm), clay (<3.9 µm), and colloid (<1 µm). Bottom sediments of rivers, lakes, and canals are regularly dredged to prevent floods during the flood peaks [1] and maintain efficient shipping traffic, and the dredging is also practiced for marine harbor docks [2]. Sediment dredged from water bodies is generally fine-grained or extremely fine-grained, mostly formed fine sand, silt, and clay minerals. The SedNet European network estimates that 200 million m³ of sediment are dredged in Europe every year. However, this estimated volume generally refers to dredging of sediments from coastal, riverine, and lake environments, not other important sources of sediments such as artificial basins and urban sediments. In fact, regular dredging operations are conducted to restore the full capacities of dams and freshwater reservoirs, which are reduced over time from the sedimentation that diminishes the basin capacity,

or damages the turbines in the case of hydropower dams. Though highly variable in dependence on the geomorphology, climatic condition, and land use, the annual amount of sediments mobilized in the watershed is in the order of 10^2 – 10^3 tons per km^2 erosion [3]. The combination of sediment quality and content is reflected in the different technologies adopted to meet the requirements of collection, transport, dewatering, and recycling on the site under dredging operations. Besides the dredging size and time frame, characteristics of the dredging site, dredging operations, and equipment depend on a number of factors on site such as water depth, type and cohesiveness of materials, presence of organic debris, chemical precipitates, levels of contamination, availability of disposal, and confined facilities [4,5]. For these reasons, dredging activities must be carefully planned, and only start when all technical requirements are met.

Sediments from rivers, dams, and urban dredging activities are generally sorted and recycled as inert materials for building activities and other industrial uses, depending on their chemical composition and mechanical properties. When possible, dredged materials and dewatered sediments are used for landscape reconstruction such as riverbank consolidation, whereas under some specific conditions, dredged marine sediment may be flown back to sea or reused for beach nourishment [6].

Urban sediment makes a specific and much less studied case. Sediments collected by the urban and suburban areas consist of particulate matter of various origin deposited on paved surfaces, including natural soil and sediments, plant and animal residues, atmospheric particles, and anthropogenic materials released by construction materials and buildings, vehicles, and combustion products. Urban sediments are remobilized climatic events and transported by wind and surface runoff and generally collected by the urban sewerage systems [7]. Preventing floods in urban areas, the water operators carry out regular maintenance practices of the water utility by dredging urban canals as well as sewerage systems, consisting of long-term dredging plans with different technologies. In the absence of dredging or insufficient maintenance of existing storm water drains for sewerage and solid waste, urban areas may experience flooding every year caused by the seasonal rains. Urban flooding is generally a catastrophic event for the city dwellers, exacerbated by the high soil sealing levels typical of urbanization, with heavy economic repercussions for the local areas.

Bottom sediments in nature act as a natural sink for water-soluble, hydrophobic, recalcitrant, and hazardous compounds emitted by point and non-point sources [8]. Therefore, dredged sites can be polluted by organic and inorganic contaminants, and sediment pollution limits the possibilities for the reuse and recycling of these materials and involves considerable problems in their management and disposal as hazardous waste [9]. Bottom sediments are a sink of persistent organic pollutants (POPs) listed in the EU Regulation 850/2004. In relation to the contamination level, in situ sediment reuse or sea disposal is generally allowed when concentration of contaminants is below the legislative threshold limits, and is not much practiced in industrial sites where sediment accumulates high concentrations of organic contaminants and heavy metals transported to the recipient water bodies by soil erosion, sewage outfalls, urban and industrial runoff, and atmospheric precipitation [10]. By considering all types of dredging activities and sites, and the diversity of the dredged environments, it is anticipated that sediments will have different physico-chemical properties, microbial communities, and pollutant types and loads. For example, sediments from the natural environment may be rich in debris and vegetation, sediments of industrial areas may be contaminated by heavy metals and organic pollutants, sediments from agricultural areas may contain high levels of agrochemicals, and sediments of urban areas may contain mud, boulders, construction debris, and also solid waste. Vast research has been conducted for setting and testing decontamination treatments as well as potential sediment reuse and recycling in different sectors, starting from decontamination reclamation and recycling technologies originally developed for the treatment of contaminated soils. The most common approaches for sediment remediation are washing, bioremediation, phytoremediation, electro-kinetic remediation, and composting, but a full

coverage of all research and technologies for sediment reclamation is out of the scope of the present paper.

The objective of this paper is to summarize the scientific evidence on the potential reuse and recycling of sediments in agriculture and landscape greening obtained in the ambit of research projects (Table 1). I present evidence from an industrial biodegradation process at real scale that produces fine sediment fractions with suitable properties as a mineral ingredient for plant-growing media, and I discuss the main reasons for hindrance of sediment recycling in agriculture.

Table 1. Sample of EU projects granted to Italian research or enterprises on sediment treatment, reuse, and technologies tested for sediment management, sediment remediation, and sediment reuse and recycling technologies. The list was created on the basis of the EU LIFE portal website (<https://ec.europa.eu/environment/life/project/Projects/index.cfm>) accessed on 20 December 2020.

Project Acronym and Year	Treatment Technology	Reuse/Recycling	Outcome
AGRIPORT (ECO/08/239065) 2009 (https://ec.europa.eu/environment/eco-innovation/projects/en/projects/agriport#results)	Sediment washing, phytoremediation	Sediment reuse and recycling for use in the environment and landscaping, preparation of technosols for growing plants	Sediment decontamination can be achieved using physico-chemical treatments and phytoremediation. Reduction of sediment treatment costs
LIFE CLEANSED (LIFE12 ENV/IT/000652) 2012 (https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4533&docType=pdf)	No treatment of dredged sediments, recycling of phytoremediated sediments	Direct use of dredged sediments for road construction, recycling of phytoremediated sediments for plant nursery	Potential reuse of dredged sediments for road construction, good performance of phytoremediated sediment for growing ornamental plants on sediment-based peat-free growing media
LIFE HORTISED—(LIFE14 ENV/IT/000113) 2014 (https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=5292)	Phytoremediation of sediments	Recycling of phytoremediated sediments for cultivation of horticultural plants	Sustainable recycling of phytoremediated sediments for growing strawberry and pomegranate, safe for health
LIFE SUBSED (LIFE17 ENV/IT/000347) 2017 (https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=6737&docType=pdf)	Phytoremediation of sediments	Recycling of phytoremediated sediments for cultivation of ornamental plants	Work in progress
LIFE AGRISED (LIFE17 ENV/IT/269) 2017 (http://www.lifeagrised.com/wp-content/uploads/2018/10/AGRISED-management-presentation-kick-off-meeting.pdf)	Co-composting of dredged sediments with green waste	Remediation of sediments for cultivation of ornamental plants	Work in progress

2. Sediment Management: The Common Options

From 1972, many international conventions have encouraged the search for alternative uses of materials dredged from water bodies (e.g., London Convention of 1972, Barcelona Convention of 1976, Helsinki Convention of 1992, OSPAR Convention of 1992), but few countries have developed specific regulations to define their reuse, whereas recycling is more developed depending on the local quality of dredged materials and the existing supply chains. Though recognized as a natural resource, dredged sediments raise specific problems in terms of management and disposal highly dependent on the sediment type,

pollution load, and disposal facilities nearby the area of dredging. These factors make it difficult to create general regulations of sediment management. The variability of the above-mentioned environmental factors is among the main reasons why the European Union (EU) has not regulated the management of dredged materials by a specific framework directive, but indirectly by the application of the EU Water Framework Directive, EU Waste Directive, and EU Directive on protected areas. In EU, the Water Framework Directive (2000/60/EC) sediments must be monitored to control the quality of all types of water bodies to ensure high water quality status, also in relation to land use and sources of pollution, though contamination threshold for sediments has not yet been adopted at the European level, but delegated to the member states, including those of transnational rivers and lakes. With the aim to reach good environmental status in EU marine environments by 2020, environmental quality standards for sediment and biota were elaborated to support the EU member states with the Marine Strategy Framework Directive (2008/56/EC). Dredging, relocation, and final deposition of sediments in surface water are regulated by the Groundwater Directive (2006/118/EC) that sets groundwater quality standards and measures to prevent groundwater pollution, but also aims to prevent flooding and mitigate droughts through the regular management of internal waters and waterways. According to the Waste Framework Directive (2008/98/EC), sediments receive the codes of the European Waste Catalogue 170505 (waste containing hazardous substances) or 170506 (non-hazardous waste), which should allow their reuse outside of the original water bodies. According to the Waste Framework Directive, the non-hazardous sediments can be reused or relocated inside the original water bodies, and the European Landfill Directive does not deal with the land application of sludge resulting from dredging operations on the soil for the purposes of fertilization or improvement, nor the deposit of non-hazardous dredged sludges alongside the water bodies from where they are dredged or their reflowing in surface waters. The Habitat Directive (92/43/EEC) and Birds Directive (2009/147/EC) aiming at protecting the biodiversity and rare biotopes and species, regulate the dredging activities of water bodies included or nearby Natura 2000 network sites to prevent impacts of the wildlife. In the latter cases, dredging operations must include sediment management options contributing to the Natura 2000 conservation objectives, for example, by creating or improving new nature sites (e.g., artificial islands, shores), and also to compensate land degradation or soil loss. Nevertheless, given the current international conventions for the protection of the marine environment and the local national and regional disposal rules, the EU will unlikely develop a sediment-specific framework directive.

In practice, the sediment management strategies and treatments should meet both sustainability and environmental safety, the two essential criteria that ensure that sediment treatment can be preferred to landfilling. In circumstances where no market exists for recycled sediments, or where sediment reuse or sediment recycling is not allowed, treatment is useless and large-scale disposal represents the sole viable option [11]. Besides the above-mentioned sediment reuse or recycling for river and lake banks consolidation, beach nourishment, strip mine reclamation, potential beneficial and productive reuses and recycling of dredged material include their use in agriculture, forestry, and horticulture [12]. One promising use of dredge material is the production of manufactured topsoil and plant-growing media that could have various applications on the market specific for professional plant nurseries, landscaping, parks, sport pitches, wetland construction, brownfield redevelopment, and natural restoration of disturbed mining areas. This potential use in agriculture and landscaping may be an additional factor that may facilitate the decision makers in the availability of sediment recycling technologies and a connected demand for recycled sediments.

3. Reuse and Recycling of Sediment in Agriculture: The Demand

The EU production of pot ornamental plants and flowers has been constant in the last decade, and EU is a net exporter of hardy perennial plants and bulbs, with a net trade surplus for live plants and floriculture products. Currently, EU hosts among the highest

density of ornamental plant production per hectare and a share of 44% of the overall world production [13]. Plant nursery production relies on the use of soilless growing media, and for the EU plant nursery sector, peat is still the prime raw material with ca. $4 \times 10^7 \text{ m}^3$ (78% of the total), with a projected 2.5-fold increase of use by 2050. Peat is an organic Histosol formed by the incomplete decomposition of plants in wetlands of cold climate, which is extracted chiefly for its use as energy biomass, but also dried and bulked for constituting growing plant media. Peatlands are endangered ecosystems protected under the aegis of the EU Directive 92/43/EC, and though peatlands are still productive, peat is a slowly renewable resource, and its use must be progressively reduced. For this reason, EU member states are progressively phasing out the use of peat for the plant nursery sector and soil amendment, and encouraging the search for reliable alternative growing media, especially those reused or recycled from waste materials. Production of peat-based growing media in EU employs ca. 11,000 workers in ca. 520 companies, for some 1.3 billion € of annual turnover [14]. Annually, an average of 5×10^4 tons of peat, pumice, perlite, and other materials are used in plant nursery soilless production, with negative impacts on the economy and the environment, related to the disturbance of the delicate ecosystems of origin and transport. Palm coir fiber- and pith-based growing media also have high environmental impact related to high initial salinity and transportation, as they are produced mainly along the southeast India and Sri Lanka coasts, and require long shipment distances for EU producers. The efforts to replace peat in growing media by various composted organic wastes [15–18] have not produced satisfactory results due to variability of the original materials and unsuitable physico-chemical properties of the final products. Only coconut fiber and coir pith, byproducts of the coconut processing, have gained a significant market share in EU as ingredients of growing media, with a volume of $5 \times 10^6 \text{ m}^3$ and an estimated sevenfold increase by 2050. The use of coir fiber- and pith-based plant growing media also causes high environmental impact due to their heavy pretreatments and transportation over long distances to reach the EU producers. The use of peat alone or in combination with other nonrenewable materials or with coir pith causes a high environmental impact [19], and it has been reported that for the plant nursery sector, peat use in the growing media is the most important source of greenhouse gas emission due to its extraction and transport [20].

From 2019, the European Regulation on Fertilizers (EU 2019/1009) shares 7 Product Function Categories (PFCs) and 11 Component Material Categories (CMCs). Inorganic fertilizers are classified on the basis of the composition, physical form, and application mode. Based on the composition, for solid inorganic fertilizers and growing media shares the PFCs are summarized in Table 2. The PFC 1(C)(I) inorganic macronutrient fertilizers, providing plants or mushrooms with N, P, K or Ca, Mg, Na, S. The PFC 1(C)(I)(a), for straight solid inorganic macronutrient fertilizer containing only one macronutrient, the minimum contents (*w/w*) must be: N 10%, P 12%, K 6%, Mg 5%, 12% Ca, S 10%, Na 1%, and not exceed 40%. For straight solid inorganic macronutrient fertilizer containing only one macronutrient, the minimum contents (*w/w*) must be: N 3%, P 3%, K 3%, Mg 1.5%, 1.5% Ca, S 1.5%, Na 1%, and not exceed 40%, and the sum of all declared macronutrient contents shall be at least 18% by mass. The PFC 1(C)(II) shares inorganic micronutrient fertilizer provides plants with B, cobalt Co, Cu, Fe, Mn, Mo, or Zn alone or in combination. Micronutrient concentrations in micronutrient fertilizer must vary from 5 for (hydro)-oxides to 10% for salt by mass. The PFC 3 shares soil improvers, fertilizing products that maintain or improve soil physico-chemical properties, microbial diversity, and microbial activity in soil.

The PFC 4 growing medium shares fertilizing products allowing growth of plants, mushrooms, and algae. For the PFC 3(B), threshold limits are set for metals and metalloids such as Cd, Cr VI, Hg, Ni, Pb, and inorganic arsenic As, whereas total Cu and Zn must not exceed 200 and 500 mg kg^{-1} , respectively. For a growing medium, pathogens must not exceed the limits set out in Table 2.

Table 2. The EU fertilizer types and the Product Function Categories (PFCs) of solid inorganic fertilizers listed in the Annex I Part I of the European Regulation on Fertilizers (EU 2019/1009).

	Composition			Physical Form		Application	
	Straight	Complex	Mix	Solid	Liquid		
	N. P. K. Ca. Mg. Na. S	NP. NPK.	Mixtures of N. P. K and other macro- and micronutrients	N. NP. NPK	N. NP. NPK + herbicides	Applied to plant	Mixed into soil
Product Function Category (PFC4) growing medium	As (40). Cd 1.5. Cr(VI) 2. Hg 1. Ni 50. Pb 120. Total Cu < 200 mg kg ⁻¹ . Zn < 500						
	<i>Salmonella</i> sp. Absence in 25 g from 5 analyzed samples. m < M = 0. Limit M = 0						
	<i>E. coli</i> or <i>Enterococcaceae</i> Max. 10 ³ CFU in 1 g from 5 analyzed samples						

The declared nutrient contents of PFC fertilizers can vary in accordance with the tolerances established in the PART III of Regulation (EC) 1069/2009 due to deviations in manufacture, distribution, and handling for analysis. The observed variability of the physico-chemical data of the recycled sediments is well within the range of the tolerances established in the above-mentioned EU regulation.

The CMCs, that is, the materials used to produce fertilizers listed in the annex II of the European Regulation on Fertilizers (EU 2019/1009) share: CMC 1 virgin material substances and mixtures, CMC 2 plants, plant parts, or plant extracts, CMC 3 compost, CMC 4 fresh crop digestate, CMC 5 digestate other than fresh crop digestate, CMC 6 food industry byproducts, CMC 7 microorganisms, CMC 8 nutrient polymers, CMC 9 polymers other than nutrient polymers, CMC 10 derived products within the meaning of Regulation (EC) No 1069/2009, CMC 11 byproducts within the meaning of end of waste (Directive 2008/98/EC), whereas the CMC 1 cannot contain natural materials obtained after an “end of waste” process.

4. Demonstrated Reuse and Recycling of Sediments in Agriculture

Sediments have an inherent fertility due to their high content of macronutrients such as C, N, P, Ca, Mg, and K, and micronutrients (e.g., Fe, Mn, Zn, Cu) [21], and the use of sediments from the Nile River overflowing as fertilizer dates back to the ancient Egypt age. In modern agriculture, the direct use of dredged sediments as fertilizer or soil amendments and as plant-growing media has been long postulated [22], as it can improve the fertility of soils under conventional farming and in the recycling of nutrients for crop production. Just as examples, in Finland and in Czech Republic, the direct reuse of sediment dredged from inner water bodies onto agricultural soils is allowed if the concentration of contaminants is below the threshold limits of the respective national legislation [23]. The direct reuse of dredged sediments is especially encouraged in the case of eutrophic water bodies, because it meets both the targets of nutrient recycling in the agroecosystem and lake and pond remediation [24,25], particularly for the recycling of P [26]. A potential reuse of lake sediments in agriculture was demonstrated by Kiani et al. [26]. Such potential reuse relies on the high chemical fertility of a river, lake, or marine sediment, which represents the natural sink of nutrients and light clayey minerals leached in the watershed [24]. Braga et al. [27] reported a successful reuse of a water reservoir sediment as fertilizer in agricultural soils depleted of fine particles and nutrients by erosion, that led to significantly lower use of chemical fertilizers and recovering of quality by the removal of nutrient-enriched reservoirs.

The direct reuse of nutrient-rich sediments can lower the impact of agriculture caused by the use of commercial P fertilizer and reduce the impact cause by the consumption of primary phosphatic rocks [28]. In addition to macro- and micronutrients, the sediment application to agricultural land can also increase the soil organic matter (SOM) content, improve the soil structure and water retention, and increase the soil cation exchange capacities (CEC), leading to an overall increase of the soil physical, chemical, and microbiological fer-

tility [22,29] and improvement of sorption properties and nutrient contents [21,22,26,29,30]. The potential beneficial direct reuse of sediments as amendment of agricultural soils depends both on the nature of the sediments and the soil properties.

As compared to sediments from the watershed, sediments of urban or industrial environments, due to anthropogenic inputs, may be of different chemical composition and may also contain contaminants such as heavy metals and POPs [31,32], which may be of concern for human health and the environment. Therefore, their direct reuse is generally not practiced, and can only occur after stringent chemical and microbiological analyses.

Differently from reuse, sediment recycling has developed only recently upon the increasing need of dredging activities for various purposes. Sediment recycling is typically based on soil washing combined with physical fractionation and recovery of the textural classes of inert materials such as stones, pebbles, gravel, and coarse sand, useful for several environmental and engineering uses. For civil engineering applications such as those of road, railway, and building construction sectors, the coarser materials are needed, whereas fine sand and silty or clayey materials are of limited use as they are rich in organic matter and, in some cases, have high inorganic and organic contaminant loads. Although the clayey materials can be agglomerated into coarser materials, these processes are costly and cause also environmental impact, thus they are generally not used. Therefore, when no further use is possible, this fraction, which generally represents 50% of the initial income mass, is landfilled. Common reclamation technologies for the recycling of the fine fraction are soil washing and bioremediation. The recovery yields and environmental quality of sediment washing are highly influenced by the percentage of silty and clayey fractions, and mainly lead to the recovery of sand and gravel, whereas the fine fraction is generally landfilled because of the high contaminant loads. In addition to the phyto- and bioremediation approaches demonstrated by the EU projects listed in Table 1, innovative and promising physico-chemical technologies such as electro-remediation and contaminant extraction with supercritical fluids have been successfully tested at pilot scale in other EU projects such as LIFE COAST-BEST (https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=COAST_BEST_Brochure.pdf), GREEN SITE (https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=3972&docType=pdf), and SEKRET (https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4545).

However, as compared to washing and thermo-chemical treatments, bioremediation can lead to the reclamation of the sediment fine-textured fractions while retaining and enhancing their fertility. Bioremediation relies on the activity of the sediment-borne microbial community under aerobic conditions (biostimulation) or by the inoculation of microorganisms capable of degrading specific compounds (bioaugmentation) in the presence of optimal aerobic and moisture conditions ensured by regular mass turning and watering. Optimal levels of organic matter mineralization and organic pollutants degradation are generally achieved and can be further enhanced by landfarming. Other sediment bioremediation options are phytoremediation using plants and microorganisms to degrade organic pollutants [33] and reduce the heavy metal content by plant uptake, and composting with organic materials to enhance the microbial activity by the optimization of the nutrient content and the addition of bulking agents, and composting with organic materials to enhance the microbial activity by the optimization of the nutrient content and the addition of bulking agents. The different bioremediation approaches depend on the sediment origin and type, and on the sustainability of the treatments, but in general, bioremediation costs can be in the order of 1/10 m³ compared to physico-chemical treatments. The technical feasibility of phytoremediation for the reclamation of sediment maritime ports and inland canals has been demonstrated in the ambit of the AGRIPORT and CLEANSED projects (Table 2). Bert et al. [34] demonstrated that contaminated marine sediments can be effectively remediated using willow and poplar plants. The technical feasibility of recycling of sediments reclaimed by phytoremediation of co-composting for the plant nursery production has been reported in the HORTISED, AGRISED, and SUBSED projects (Table 1).

Mattei et al. [33] showed that phytoremediated marine sediments could completely replace peat as a growing medium for ornamental plants, and it has been demonstrated that sediment co-composting with organic wastes produces fertile growing media for growing ornamental plants [33,35]. The vast literature on the safe reuse of recycled sediments in the sector of plant nursery production and the large number of demonstrations even at market scale fulfill the criteria of the End of Waste EU Directive. In fact, the dredged materials can be recycled because concentrations of inorganic and organic pollutants do not exceed the legislation thresholds, and they comply with technical specifications of the common materials they replace while reducing the emissions as assessed by the Life Cycle Analysis [36].

Use of sediments and other natural minerals as growing media has been also proposed by EU stakeholders and included in the proposals for the revision of the Ecolabel criteria for soil improvers and growing media by the Joint Research Center (JRC) of the EU [37]. However, as stated in paragraph 4, sediments are excluded by the CMCs of EU fertilizers, regardless of the potential demand in specific agricultural sectors. Therefore, while efficient industrial sediment recycling physico-chemical and biotechnologies developed in response to the increasing needs of dredging activities may produce materials with high fertility, the new EU regulation on fertilizers still limits the circularity of these activities.

5. Sistemi Ambientali: A Case Study at Industrial Scale

The Sistemi Ambientali company, located in Calcinato (Bergamo, Northern Italy), is a company active in the sector of transport and treatment of hazardous and non-hazardous waste, specialized in management of canals and water streams, sanitization activities, and other environmental management interventions. Bergamo Province hosts 750,000 inhabitants on 80,000 ha, and the annual amount of sediments dredged by the regular annual maintenance of 1500 linear km of irrigation canals to ensure freshwater for agricultural activities and prevent hydrogeological risk by the local Authority for Land Reclamation is on average 20,000 metric tons. The common sediment treatment and reclamation in the area are bioremediation and soil washing, with recovery yields highly influenced by the percentage of silty and clayey fractions in the dredged materials. Sistemi Ambientali developed a process based on sequential texture class fractionation, chemical analysis, and maturation of the fine sediment fraction by dynamic biopiles, for a potential sediment reclamation in the order of 98% of the processed dredged materials. Since 2011, the company has operated a plant designed for the treatment and recovery of earthy matrices such as sediments dredged from surface water bodies and during maintenance operations, scheduled by the Authority for Land Reclamation of the Bergamo Province, to maintain their hydraulic capacity from ca. 200 canals and dredging ponds. During the sediment treatment process, the incoming materials are pretreated for the separation of coarse inert materials according to the UNI EN 13242; the fine fraction is then sent to a dynamic biopile treatment for the degradation of the organic pollutants.

In line with the International Conventions on sediments management and the EU Directives on waste management and environmental protection, Sistemi Ambientali has conducted research and development activities to optimize the recovery process of inert gravel and sand and of fine-textured sediment fractions, and currently the potential recycling achieves 98% of the processed. However, while the gravel and sand fractions are re-used by the local construction industry, the organic matter-rich fine sediment fraction amounting to more than 40% of the initial volume has currently limited practical use in building activities, is classified as hazardous waste, and should be landfilled with high environmental impact, and costs in the order of Eur 100 per ton. The dynamic biopiles are prepared by Sistemi Ambientali after mechanical grain size fractionation. Biopiles are formed by windrows of 1500 m³ build-up at the industrial premises, weekly turned, and monitored for humidity, temperature, and degradation trends of organic pollutants and *Escherichia coli* CFU counts during the first two weeks and at the end of the bioremediation process, whereas the *Salmonella* sp. were monitored in previous years (2004–2006), and

they were absent in 25 g of bioremediated fine sediments. The physico-chemical analyses were conducted by certified chemical laboratories for the quantification of the parameters on the solid phase and the leaching test requested by the Italian environmental legislation (D.Lgs 152/06) with the standard methods prescribed therein. In addition to the minimum legislation parameters, Sistemi Ambientali also regularly analyzes the total heterotrophic culturable bacteria and the *E. coli* estimated by the colony forming units (CFU) using the USEPA (mss2003) method, and the germination and root elongation tests of lupin, watercress, and soybean with the method OECD 208/2006.

The thermophilic phase has a duration of 7–10 days, and the peak temperature reached by the biopiles is generally 10 °C over the ambient temperature and the average moisture content is 15%. Therefore, the bioremediation process is cold/mesophilic and is normally completed within 120 days. At the end of the bioremediation process, all materials fulfill the criteria for environmental recycling according to the Italian environmental legislation. The average moisture content and the bulk density of the fine sediments at the end of the bioremediation process are 16% and 1.38 g cm⁻³, respectively. The main physico-chemical properties of the recycled sediment fine fraction produced by 10 dynamic biopiles produced by the industrial activity during the years 2018 and 2019 are reported in Table 3.

Table 3. Main physico-chemical properties of the Sistemi Ambientali sediments produced by the dynamic biopile technology.* Data resulting from the leaching test UNI EN 12457-2 2004 + UNI EN ISO 10304-1 2009.

	Sand (%)	Silt (%)	Clay (%)	pH *	EC * (μS cm ⁻¹)	DOC * (mg L ⁻¹)	NO ₃ ⁻ -N * (mg L ⁻¹)	SO ₄ ²⁻ * (mg L ⁻¹)
N° biopiles	10	10	10	10	8	10	10	10
Average	66.1 ± 10.4	13.4 ± 7.6	24.0 ± 6.4	7.90 ± 0.6	199 ± 77	39.8 ± 6.8	31.2 ± 5.9	61.0 ± 20.2
Min	58	6	9	7.16	169	26.0	5.9	28
Max	85	23	29	8.50	364	47.6	45.0	133

The sediments show typical texture, pH, and EC values of reclaimed sediments dredged from inland areas. For both solid phase and leaching, organic pollutant classes such as total and heavy (C > 12) hydrocarbons, polychlorinated hydrocarbons (PCB), benzene, toluene, ethylbenzene and xylene (BTEX), phenols, polycyclic aromatic hydrocarbons (PAH), and agrochemical such as DDD, DDE, DDT atrazine, endrin, and dieldrin were below the concentration limits for sediment reuse in urban and industrial areas according to the Italian environmental legislation. Concentration of total heavy metals and metalloids is reported in Table 4. All of the elements were below the concentration limits for sediment reuse in urban and industrial areas according to the Italian environmental legislation and for the concentration limits set by the EU regulation 2019/1009 for plant growing.

Attention should be paid to Cd concentrations that were detected at total Cd concentrations >1.5 mg kg⁻¹ in 3 out of 10 bioremediated sediments, and for Zn concentrations that were >500 mg kg⁻¹, in 4 out of 10 biopiled materials, and some concern is also raised by organo-tin compounds (Sn_{ORG}) detected at concentration >0.5 mg kg⁻¹ in 4 out of 10 samples. Moreover, though in bioremediated sediments the *Salmonella* CFUs was absent in years 2004 and 2005, this pathogenic microorganism must be monitored again in the future, as requested by the EU and also national legislation on growing media.

The plant germination and root elongation tests showed average values of 104.0 (±5.2) and 105.7 (±6.1), respectively, higher than the 96% requested for growing media by the EU regulation on fertilizers, indicating no toxicity and high fertility of the bioremediated sediments.

Overall, the data obtained by the chemical and eco-toxicological analyses demonstrate that there is potential for recycling of the bioremediated sediments as ingredients of growing media for growing ornamental plants and as technosols for damaged or degraded forest areas, in line with the literature on the topic and the evidence from the several EU projects listed in Table 1. However, as the potential use of the recycled sediments in agriculture is not allowed by the current legislation, the Sistemi Ambientali company is

able to recycle the biopiled materials only as technosol for the creation of green space in industrial and commercial sites. This case study based on the normal activity of a company on the market of environmental technologies demonstrates the potential feasibility of full recycling of the reclaimed sediments if their use in selected non-food agriculture would be a welcome practice. A safe recycling of the fine nutrient-rich sediment fraction can bring significant environmental and financial benefits for companies with business in the different sectors of sediment dredging and ornamental plant production offering cost-effective new products. The sediment treatment process of Sistemi Ambientali also shows potential for improving the technical properties of the bioremediated sediments, for example, in the reduction of the bulk density which can be lowered by up to 0.75 g cm^{-3} by dry sieving after the bioremediation process, and in terms of biological fertility by the enrichment with nutrients and inoculation of biostimulant microorganisms to produce tailored earthy matrices through innovative biotechnologies, with the creation of new jobs and value in environmental biotechnologies. Interestingly for the aims of this paper, the CMC 6 food industry byproducts include lime from drinking water production among the other substances, a residue rich in CaCO_3 produced by the purification from groundwater or surface water for the production of drinking water. Finally, as the CMC 10 “derived products within the meaning of Regulation (EC) 1069/2009”, the recycled sediments are materials that have reached the end point in the manufacturing chain of sediment management and reclamation. Of course, recycled sediments must fulfill the general labeling requirements, which may not be obvious due to the variability of the sediment physico-chemical properties depending on the dredged areas.

Table 4. Concentration of metals and metalloids in the Sistemi Ambientali sediments produced by the dynamic biopile technology compared to the concentration limits for recycling in the urban and industrial environment according to the Italian legislation and the concentration limits in the plant-growing media according to the EU regulation 2019/1009. * Cd concentrations > 1 detected in 3 out of 10 samples. ** Organo-Tin concentrations > 0.5 detected in 3 out of 10 samples. ND indicates value not determined. *** Zn concentrations > 500 detected in 4 out of 10 samples.

Element	Method	Concentration (mg kg^{-1})	Range (Min–Max)	Limits in Relation to Site Use (DLgs 152/06)		Growing Media (EU Regulation 2019/1009)
				Urban	Industrial	
Sb	EPA 3051 A 2007 + EPA 6010 D 2014	<0.5	ND	10	30	
As	EPA 3051 A 2007 + EPA 6010 D 2014	15.2 ± 3.7	9.3–19.0	20	50	<40
Be	EPA 3051 A 2007 + EPA 6010 D 2014	<1	ND	2	10	
Cd*	EPA 3051 A 2007 + EPA 6010 D 2014	4.6 ± 1.6 *	<1–5.2 *	2	15	<1.5
Co	EPA 3051 A 2007 + EPA 6010 D 2014	8.6 ± 2.9	2.0–9.6	20	250	
Cr _{TOT}	EPA 3051 A 2007 + EPA 6010 D 2014	40.3 ± 16.3	8.0–56.0	150	800	
Cr(VI)	CNR IRSA 16 Q 64 Vol 3 1985	<1	ND	2	15	<2
Hg	EPA 3051 A 2007 + EPA 6010 D 2014	<1	ND	1	5	<1
Ni	EPA 3051 A 2007 + EPA 6010 D 2014	27.9 ± 12.5	53.0–8.0	120	500	<50
Pb	EPA 3051 A 2007 + EPA 6010 D 2014	99.3 ± 50.3	13.0–180	100	1000	<120
Cu	EPA 3051 A 2007 + EPA 6010 D 2014	59.1 ± 24.5	8.0–93.0	120	600	<200
Se	EPA 3051 A 2007 + EPA 6010 D 2014	<1	ND	3	15	
Sn _{ORG} **	EPA 3051 A 2007 + EPA 6010 D 2014	7.9 ± 2.8	<0.5–12.0	1	350	
Tl	EPA 3051 A 2007 + EPA 6010 D 2014	<1	ND	1	10	
V	EPA 3051 A 2007 + EPA 6010 D 2014	44.8 ± 22.1	7.0–53.0	90	250	
Zn ***	EPA 3051 A 2007 + EPA 6010 D 2014	541 ± 263	92–1030	150	1500	<500

6. Conclusions

The main EU Directives dealing with sediment management concern water, waste, and landfills, and therefore mainly focus on the impact of sediment reuse or dumping, whereas sediment recycling is seldom on the environmental public agenda. Consequently, although sediment recycling has been a staple of environmental sustainability for decades, it does have some downsides, as the fine-textured materials can be difficult in civil engineering uses due to their poor mechanical properties. This fraction enriched in organic matter and macro- and micronutrients could be recycled in some non-food agricultural sectors, for example, as an ingredient of growing media or as backfill soils of plant nurseries.

production of ornamental plants, and preventing the use of primary raw materials such as peat pumice and perlite, characterized by high environmental impact, and counteracting the soil loss. This has been undisputedly demonstrated by several EU granted projects and vast scientific literature. In spite of the recent advances, companies acting on the market of sediment dredging and environmental technologies, like, for example, Sistemi Ambientali in Italy, can nowadays produce sediment fractions with low contaminant loads that comply with environmental and agricultural legislations. However, while organic pollutants can be effectively biodegraded, attention must be paid to heavy metals, especially Cd and Zn, that may reach concentrations higher than those set by the EU regulation on fertilizers. Currently, while the recycled sediments display suitable technical properties which can be even further improved, the new EU regulation on fertilizers excludes the sediments from the component material of EU fertilizers, thus preventing one of the largest potential beneficial uses that may improve the quality of degraded agricultural soils and close the nutrient cycles in the agro-ecosystems. In fact, if not recycled in agriculture, nutrients in sediments are allocated in non-agricultural environment or, even worse, landfilled. Therefore, in my opinion, unpolluted nutrient-rich recycled sediments as “earthy matrix” CMC of the EU regulation on fertilizers should be reconsidered.

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