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Article

Testing the Feasibility of Usumacinta River Sediments as a Renewable Resource for Landscaping and Agronomy

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Abstract: Fluvial sediment recycling in agronomy is a relatively recent development, as sediment fertilizing potential for crops is unexplored. Freshwater sediments can act as fertilizer and improve the aeration of soils to increase the yield of crops, support vegetation for landscaping, and provide protective cover against erosion. This study focuses on the investigation of the agronomic potential of Usumacinta River sediments. The pH of the sediments is around 8.5, which is slightly alkaline. The organic matter content is low (5.7%). The sodium absorption ratio is 1.2 and the electrical conductivity is low (0.02 mS/cm). These values indicate that sediments are nonsaline, which is essential for the growth of crops and vegetation. The environmental characteristics of sediments show that the heavy metals, polycyclic aromatic hydrocarbon (PAH), and polychlorinated biphenyl (PCB) pollutants in sediments are below the recommended thresholds. In addition, sediments from the Usumacinta River contain minerals such as potassium and iron oxides that are helpful in improving the biological and nutritional characteristics of the soil. Furthermore, the pH, granulometry, mineralogy, organic matter, and carbonate contents of the Usumacinta River sediments are similar to agronomic soils. The Usumacinta River sediment's potential for agronomy was practically investigated by sowing ryegrass (*Lolium perenne*) in a greenhouse by using the local climatic conditions and mixing sediments with potting soil. Three soil compositions were used to evaluate the germination and growth of ryegrass. The soil compositions were 100% potting soil (C1), 50% sediments + 50% potting soil (C2), and 100% sediments (C3). The growth rate of ryegrass was evaluated by monitoring the increase in grass height and production of fresh biomass. The germination of ryegrass was similar in all three compositions. The growth of ryegrass and production of fresh biomass were the most significant with 100% potting soil (0.25 kg/m²), somewhat less with sediment mix (0.18 kg/m²), and were the least significant with 100% sediments (0.05 kg/m²). The mixture of potting soil and sediments shows similar growth to 100% potting soil. The ryegrass seed germination, growth, and production of fresh biomass with the mixture of sediments gave encouraging results, and underlined the potential of sediments for soil amendments for agronomy and protective developments, such as limiting riverbank erosion, gardening, and landscaping.

Keywords: fluvial sediments; sustainable recovery; soil fertilization; riverbank erosion; topsoil



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1. Introduction

Sediments are dredged from rivers, lakes, and ports to smoothly run navigation operations, maintain courses, and control floods. Millions of tons of sediments are generated annually across the globe. Once dredged, sediments are considered a waste. The land storage of sediment waste is becoming costly. Therefore, the reuse of sediment helps to eliminate dredged sediment waste through their valorization in different applications.

Sediment recovery helps to minimize the burden on natural resources such as sand and aggregate. The volume of dredged sediments and their characteristics are important for their recovery and to meet the increasing demands of industry. Every year in France, 50 million m³ of marine sediments are dredged, while 6 million m³ of estuarine sediments are dredged [1]. In the Rouen and Le Havre regions of France, 6–7 million m³ of dredged sediments are immersed in the sea [2]. On the other hand, natural resource consumption is increasing. For example, the construction sector of France consumes around 0.85 billion tons of sand annually [3].

Sediments near industrial areas and mining sites are often lightly or heavily polluted and need special attention before their reuse. Pollutants such as heavy metals (Hg, Ni, Cr, Pb, and Cu) and organic compounds (polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs)) result from industrial activities in the proximity of water bodies. The valorization of contaminated sediments is difficult, and is only possible after their treatment, which removes contaminants [4]. Inert sediments can be recovered for different applications such as roads, landscaping, backfills, dikes, and construction materials [5,6]. Sediments can partially or fully replace traditional materials in construction materials. The agronomic recovery of sediments to improve the structure of soils lacking nutrients and organic matter is interesting from an ecological and economic viewpoint. Sediment recovery in development works such as landscaping, the creation of green areas, the restoration of sites, and the reconstitution of the agronomic soil can be both an economical and sustainable solution to manage topsoil degradation and sediment management and recovery [7].

Sediments consist of sand, clay, and silt. Mixing of sediments with soil increases the aeration of soil by improving soil structure, providing nutrients, and improving the cation exchange capacity of soils [8]. Agronomic soil's first 30–40 cm thick layer is usually rich in organic matter (OM) and suitable for vegetation. However, the overcultivation, erosion, and compaction of soil and excessive reuse of fertilizers lead to soil degradation and loss of crop yield, along with environmental drawbacks such as water pollution and the sedimentation of rivers and streams. Furthermore, the presence of salt in the soil has an adverse impact on the growth of vegetation, as it becomes hard for plants to absorb water from the soil [9]. Soils amended with sediments obtain necessary minerals from sediments, and for these soils, a smaller quantity of commercial fertilizers can be sufficient. The mixing of sediments and soil improves soil fertility and crop yield and quality, as soils are enriched by the nutrients in sediments. Nitrogen, phosphorous, and potassium are some important nutrients that are responsible for plant growth. The micronutrients in soil and sediments helpful in the growth of plants are Fe, S, Mn, Mg, B, etc. [10]. In addition, compacted soil's water-holding capacity can be improved via soil amendment through mixing with sediments [11].

The potential of sediment reuse in agronomy is highlighted through experimentation in different research studies, which mixed different percentages of sediments with agronomic soils ranging from 0, 5, 10, and up to 100%. The quantity of sediments depends on the sediments' characteristics, cultivation conditions, and types of crops [10,12–14]. Sediments can also be reused for landscaping to build green spaces, embankments, and walkways. Sediments with suitable characteristics help to stabilize the soil, control erosion, and support vegetation.

The recovery of sediments as a resource supports the local circular economy of the region due to their reuse in public works and agronomy, thereby decreasing the use of quarry sand, soils, and chemical fertilizers. Sediments, once dredged, are considered waste, and their transportation is costly. In addition, the presence of water in sediments makes their transportation further complicated. Sediments from urban areas are dumped in landfills which are usually 20 to 30 km outside the cities. The transportation cost of sandy sediments through trucks is around USD 0.02 per cubic meter per km [15]. Reusing sediments in nearby areas reduces transportation and environmental impacts such as carbon emissions due to reduced distance. Moreover, soils are degraded with continuous

use of chemical fertilizers. Nutrient (nitrogen, phosphorous, and potassium)-rich sediments can be used as organic fertilizers to reduce the consumption of chemical fertilizers and save money. Nikafkar et al. 2023 [16] observed that the economic value of nitrogen, phosphorous, and potassium in Latian Dam (Iran) sediments is around USD 122, USD 721, and USD 946 per ton, respectively.

The objective of this study was to investigate the characteristics of Usumacinta River sediments to see their potential for local applications such as agronomy, landscaping, soil aeration, and erosion prevention for embankments. Agronomic characteristics of Usumacinta sediments were investigated followed by mixing with potting soil to sow ryegrass in the greenhouse. Germination, growth of ryegrass, and production of fresh biomass were monitored to evaluate the possibility of Usumacinta River sediments recycling in landscaping and agronomic applications.

2. Materials and Methods

2.1. Usumacinta River Sediments

Usumacinta River sediments were dredged from Jonuta (J) town in the Tabasco state of Mexico with shovels and buckets and sealed into hermetic barrels of 100 kg. Three sediment barrels of 100 kg were dredged from the site and transported to the laboratory. The absence of metropolitan areas, major mining operations, and industrial areas near the dredging sites makes the sediments less likely to be contaminated, which is the main hurdle for sediments reuse in agronomy. The sediments' environmental characteristics were examined through different tests to see the presence of contaminants. Heavy metals presence in sediments was observed with inductively coupled plasma/atomic emission spectrometry (ICP/AES) [17]. Polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) were determined with chromatography and spectrometry using the French standard [18]. Environmental characterization was followed by physicochemical and mineralogical analysis to find the grain size, organic matter, carbonate content, pH, and presence of minerals and oxides. The grain size of sediments was determined with a laser particle sizer [19]. Organic matter in sediments was determined by burning the sediments at 450 °C after French recommendations [20]. The percentage of calcium carbonate in sediments was determined with the Bernard calcimeter method [21]. pH and electrical conductivity of sediments were measured with pH and conductivity meters conforming to standards [22,23]. The presence of different minerals and oxide in sediments were observed with X-ray diffraction. A blue methylene test was also performed to see the presence of clay minerals and the cation exchange capacity of sediments [24]. Sodium absorption ratio (SAR) was determined through inductively coupled plasma/atomic emission spectrometry (ICP/AES) by the quantity of calcium and magnesium in accordance with French recommendations [17]. The following formula was used to find the SAR value.

$$\text{SAR} = \frac{\text{Na}}{\sqrt{0.5 * (\text{Ca} + \text{Mg})}} \quad (1)$$

where Na, Ca, and Mg are expressed in mg/kg.

2.2. Potting Soil

Sediments were mixed with commercial potting soil to increase the fertility of sediment–soil composite and observe the performance of sediments at different mix ratios. The potting soil used is specially designed for plants and vegetation in homes and lawns and it has the commercial name of *Terreau* in France. This soil is high in organic matter and consists of peat, fibers, compost, and minerals. Figure 1a shows the sediments, and Figure 1b shows the potting soil used.

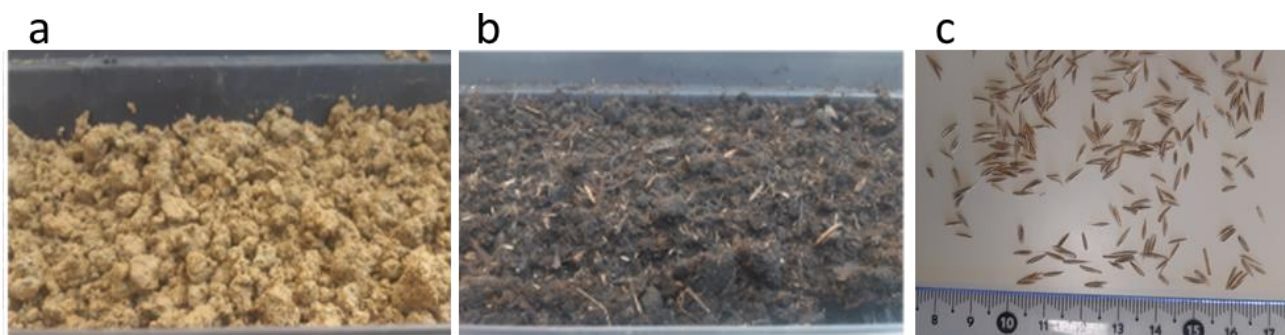


Figure 1. Usumacinta River sediments (a), potting soil (b), and ryegrass seeds (c).

2.3. Rye Grass

Ryegrass has been used in experimental studies to explore the possibility of sediment reuse in agronomy, landscaping, control of erosion for dykes, etc. [8,10,25]. Ryegrass was used in this research to evaluate the potential of sediments for agronomy and landscaping. Ryegrass used in this study has the scientific name *Lolium perenne* and the commercial name *Gazon Anglais Carrefour*. Figure 1c shows the seeds of ryegrass used.

2.4. Greenhouse Testing Conditions

The testing conditions of a greenhouse have a significant influence on the germination and growth of vegetation. Some important parameters that influence the growth and germination of ryegrass in the greenhouse are temperature, types of seeds, depth of buried seeds, the salinity of the soil, and watering of grass [26,27]. Some experimental studies mix sediments with agronomic soils to grow crops in controlled and field conditions for a specific time duration ranging from a few weeks to a few months. Experimentation in controlled conditions allows the regulation of the temperature and relative humidity of the greenhouse. Table 1 shows the summary of testing conditions observed in the literature for the recovery of sediment in agronomy.

Table 1. Dredged sediments and cultivation conditions.

Sediments	Sediments (%)	Crops	Conditions	T * (°C)	RH ** (%)	Time	Reference
Lake	75 cm thick layer	Ryegrass	Farmland	-	-	243 days	[10]
Reservoir	5, 10, 30, 50, 100	Maize	Farmland	-	-	70 days	[12]
Lake	0, 10, 20, 100	Soybean	Greenhouse	31.5	43.6	123 days	[13]
River	0, 10, 25, 50, 75, 100	Cucumber	Chamber	25	-	4 weeks	[14]
Lake	5, 10, 20	Lettuce	Greenhouse	-	-	2 months	[28]
Lake	12–18 inch layers	Corn	Farmland	-	-	4 months	[29]

Note: * T = temperature; ** RH = relative humidity; 1 inch = 2.54 cm.

Table 1 shows that the percentage of sediments in soil has significant variation and ranges from 0% to 100%. The temperature of the greenhouse is 25 and 31.5 °C, while the duration of experimentation ranges from a few weeks to a few months.

In this study, Usumacinta River sediments were mixed with potting soil to cultivate ryegrass. Local climatic conditions of Tabasco, Mexico, were replicated for greenhouse testing. The temperature of the greenhouse was kept at 30 °C, which is similar to the average local temperature and the temperature used in other studies, as shown in Table 1. The average relative humidity of the Tabasco region fluctuates between 70% and 90% throughout the year. The relative humidity of the greenhouse was initially set at 90% and then decreased to 70%.

2.5. Soil–Sediment Mix

Usumacinta sediments and potting soils were mixed at different ratios to observe the sediment's performance. Mixtures of 100% sediments, 50% sediments, and 0% sediments were used to evaluate the performance of sediments. Similar mixtures of compositions have been used in studies for soil amendments and germination of various plants [12,14,30]. Soil and sediment mixtures were filled in plastic containers of size $20 \times 20 \times 70 \text{ cm}^3$ with a drainage hole at the bottom as shown above in Figure 1a,b.

2.6. Sowing of Ryegrass

Ryegrass seeds were buried at a depth of 3–5 cm in a soil–sediment mixture. Watering of ryegrass was performed on the first day, followed by watering every week. Growth and germination of ryegrass were observed for several soil compositions at different time intervals to evaluate the sediment's behavior in the soil mix. The height of ryegrass was measured at continuous intervals to monitor its growth for nearly two months (66 days). Ryegrass was cut to 5 cm in height after every few days when its height reached 10 cm. The height of adult ryegrass noted in experimental studies ranges from 30 cm to 40 cm [31]. Variation in fresh biomass obtained by trimming the grass was also observed. Soil compositions with 100% potting soil (C1) (a), 50% potting soil (C2) (b), and 100% sediments (C3) can be seen in Figure 1a–c.

3. Results and Discussion

3.1. Sediments and Soil

The environmental characteristics of sediments were evaluated by observing the presence of contaminants and heavy metals. Heavy metal contamination in Usumacinta sediments is shown in Table 2. Heavy metal contamination is considerably lower than the recommended threshold (N1, N2) in French standards [32], except for Ni in Table 2. Ni has resulted from the mining activities upstream of the Usumacinta River in Guatemala. However, Ni quantity varies with the season, and sediment dredging in dry seasons is helpful to minimize the percentage of Ni. Organic pollutants such as PAHs and PCBs were also investigated. Table 2 shows the presence of PAHs and PCBs in Usumacinta River sediments, which is negligible.

Table 2. PAHs and PCBs values of Usumacinta River sediments [33].

PAHs (mg/kg)	J	N1	N2	PCB (mg/kg)	J	Metals (mg/kg)	S1	J
Naphtalene	0.002	0.16	1.13	PCB c 28	<0.001	As	30	5.19
Acenaphtylene	<0.002	0.02	0.26	PCB c 52	<0.001	Cd	2	<0.4
Acenaphtene	<0.002	0.04	0.34	PCB c 101	<0.001	Cr	150	131
Fluorene	<0.002	0.02	0.28	PCB c 118	<0.001	Cu	100	20.5
Phenanthene	0.003	0.08	0.59	PCB c 138	<0.001	Hg	1	<0.1
Anthracene	0.004	0.24	0.87	PCB c 153	<0.001	Ni	50	256
Fluoranthene	<0.002	0.6	2.85	PCB c 180	<0.001	Pb	100	11.3
Pyrene	0.004	0.5	1.5			Zn	300	40.2
Benzo anthracene	<0.002	0.26	0.93					
Chrysene	<0.002	0.38	1.59					
Benzo pyrene	<0.002	0.43	1.01					
Benzo perylene	<0.002	1.7	5.56					
Indono pyrene	<0.003	1.7	5.56					

Note: J = Usumacinta River sediments dredged from Jonuta site; PCB c = PCB congener; N1 = level 1 of contaminants in sediments; N2 = level 2; S1 = threshold of contaminants in soils.

Grain size analysis of Usumacinta sediments shows that these sediments have higher silt content (around 62%) and are within the category of clayey soil according to GTR classification [34]. Granulometry has a substantial influence on the porosity, aeration, and water-retention capacity of sediments [35]. The texture of sediments shows that these

sediments are silt loam [36]. Usumacinta River sediments are well sorted, with higher permeability and porosity, which is essential to circulate water and air [37].

The organic content of sediment is 5.7% and they are categorized as low organic sediments [38]. The higher organic content of the soil increases the fertility of the soil. The pH value of Usumacinta sediments is 8.5, which indicates that the sediments have an alkaline nature. However, studies have shown that germination of ryegrass is not much impacted by pH values between 5 and 10 [27]. The alkalinity of sediments is usually caused by carbonate minerals. Dolomite and calcite are carbonate minerals in Usumacinta sediments. The carbonate content of sediments shows that the sediment's nature is nonmarly [21]. The electrical conductivity (EC) of Usumacinta sediments is very low, which is important for plants. Usually, saline soils have higher EC, and the maximum allowed limit for EC in soils is 1 mS/cm [39].

The study of oxides in sediments is helpful to know their composition and their behavior in interaction with the soil. Table 3 shows that SiO₂, Al₂O₃, and CaO are the main oxides in Usumacinta sediments. Silica and alumina are mainly associated with sand and clay in sediments. In addition, primary nutrients, such as potassium oxide, and micronutrients, such as iron oxide, are also observed. These nutrients are responsible for the growth of plants. The sodium absorption ratio (SAR) of sediments was measured with the quantity of Na, Ca, and Mg in sediments. Table 3 shows that the SAR value of Usumacinta sediments is around 1.2. The salinity of Usumacinta River sediments was assessed with sodium absorption ratio (SAR) and electrical conductivity (EC) on the salinity chart [40,41], which shows that Usumacinta sediments are nonsaline. The salinity of sediments must be low, as in saline sediments it is difficult for plants to obtain water. The pH value of Usumacinta sediments is just at the limit between the alkaline and nonalkaline fields.

Table 3. Physicochemical characteristics of Usumacinta sediments and potting soil.

Usumacinta Sediments										
J	pH	OM (%)	EC (mS/cm)	CaCO ₃ (%)	Clay (%)	Silt (%)	Sand (%)	CEC (meq/100g)		
	8.5 ± 0.1	5.7 ± 0.2	0.02 ± 0.0	8.5 ± 0.2	13.4 ± 0.0	62.5 ± 2.2	24.1 ± 2.3	35.7 ± 1.5		
Oxides and SAR of Sediments										
J	SiO ₂ (%)	Al ₂ O ₃ (%)	CaO (%)	TiO ₂ (%)	Fe ₂ O ₃ (%)	K ₂ O (%)	Na (mg/kg)	Ca (g/kg)	Mg (g/kg)	SAR (-)
	56.3 ± 1.4	16.1 ± 2.1	6.4 ± 0.5	1.9 ± 0.3	16.1 ± 2.8	2.6 ± 0.7	241.0 ± 27.0	59.8 ± 5.1	15.4 ± 0.5	1.2 ± 0.1

Note: ± in the table indicates the standard deviation; J = Jonuta sediments; OM = organic matter; EC = electrical conductivity; SAR = sodium absorption ratio; CEC = cation exchange capacity.

The presence of minerals in Usumacinta River sediments was observed with XRD. Clay and carbonate minerals are some important minerals for sediment reuse in agronomy. Table 4 shows the presence of different minerals in the Usumacinta River sediments.

Table 4. Minerals in Usumacinta River sediments.

Sediment	Mnt (%)	Ilt (%)	Vrm (%)	Kao (%)	Qz (%)	Cal (%)	Dol (%)	Bt (%)	Crs (%)	Or (%)	Ano (%)	Ab (%)	Others (%)
J	10 ± 0.7	6.4 ± 1.5	17.1 ± 0.4	4.9 ± 0.2	21.4 ± 1.3	2.2 ± 0.7	10.1 ± 2.2	7 ± 0.1	1.6 ± 0.6	5.3 ± 0.4	9.6 ± 1.7	4.3 ± 0.3	5 ± 2.8

Note: Mnt = montmorillonite; Ilt = illite; Vrm = vermiculite; Kao = kaolinite; Qz = quartz; Cal = calcite; Dol = dolomite; Bt = biotite; Crs = cristobalite; Or = orthoclase; Ano = anorthoclase; Ab = albite; Others = nonidentified minerals.

Table 4 indicates that the main clay minerals in Usumacinta sediments are montmorillonite, illite, vermiculite, and kaolinite, while calcite and dolomite are the main carbonates.

Vermiculite is water-sensitive clay and exhibits swelling on interaction with water, while kaolinite is dimensionally stable and less sensitive to water [42]. Clay minerals constitute nearly 38% mass of sediments; they typically contain the nutrients necessary for plant growth and are suitable for soil that has experienced erosion [43]. The pH of Usumacinta sediments is 8.5, while their texture is silty. The literature on sediment reuse in agronomy shows that the pH value of sediments used for agronomic applications ranges from 7 to 9.9, while the texture of sediments varies from sandy to clayey [8].

Usumacinta River sediments were mixed with potting soil specially designed for agronomic applications and rich in organic matter. The characteristics of the potting soil are summarized in Table 5.

Table 5. Characteristics of potting soil and sediments.

Soil	Dry Matter (%)	OM (%)	EC (mS/cm)	WRC (mL/L)	pH
Potting soil	38.0	72.0	0.36	780	6.5
J4 sediments	78.1	5.7	0.02	-	8.5

Note: WRC = water-retention capacity; OM = organic matter; EC = electrical conductivity.

The conductivity of potting soil is similar to the Usumacinta River sediments; however, the amount of organic matter is very high. The pH value of the soil is lower than the sediments and it has a slightly acidic nature.

3.2. Germination and Growth of Ryegrass

Ryegrass was cultivated in the greenhouse at controlled conditions. The germination of ryegrass seeds started on day 4; however, complete germination happened on day 5. Different treatments, i.e., 100% potting soil (C1) (a), 50% potting soil (C2) (b), and 100% sediments (C3) (c), and germination of ryegrass are shown in Figure 2.

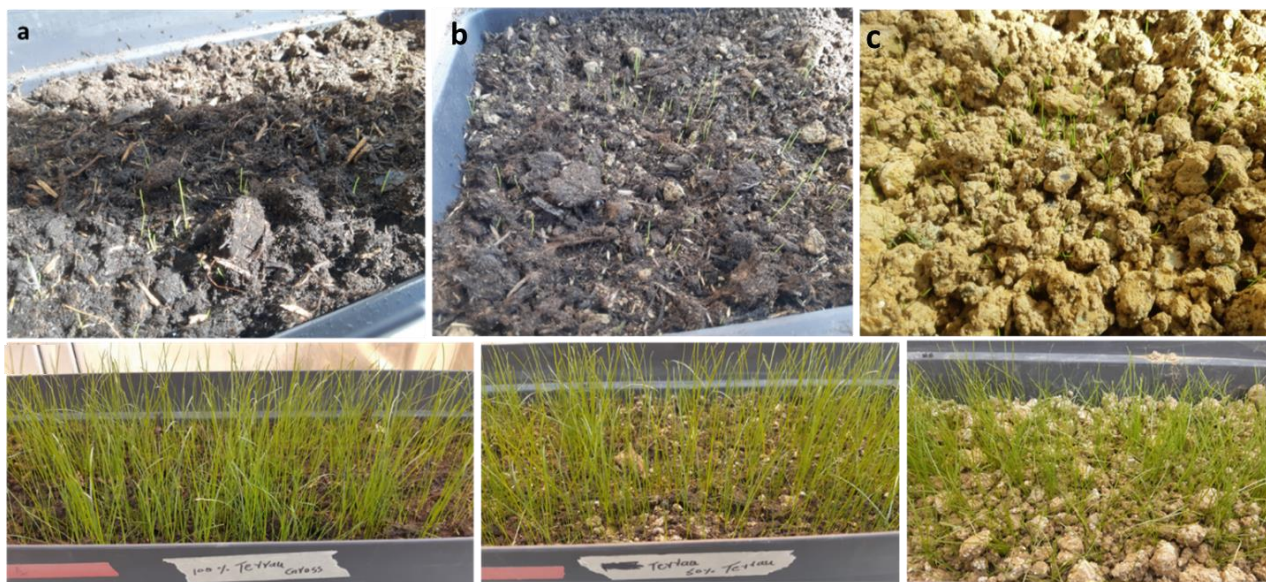


Figure 2. Germination and growth of ryegrass with compositions C1 (a), C2 (b), and C3 (c).

The growth of ryegrass increases with increasing time. The increase in grass height was observed for nearly two months in the greenhouse. Variation in ryegrass height with time is shown in Table 6.

Table 6. Ryegrass growth with time.

Days	h _{C1} (cm)	h _{C2} (cm)	h _{C3} (cm)
0	0	0	0
5	Germination	Germination	Germination
9	4	3	3 to 4
12	7	6	4 to 5
15	9	7	5 to 6
17	11 *	10 *	6 to 7
19	8	7	6 to 7
22	15 *	13 *	7 to 9
23	7	6	9 to 11 *
24	11 *	10 *	5 to 6
27	9	8	7 to 8
29	12 *	11 *	9 to 10
36	14 *	12 *	10 to 11 *
38	9	8	5 to 6
43	16 *	15 *	6 to 7
45	8	7	7 to 8
47	13 *	12 *	9 to 11 *
55	12 *	11 *	6.5
60	9	9	7.5
66	12 *	11 *	7.5

* At this height, ryegrass was cut to the height of 5 cm.

Table 6 shows that the germination of ryegrass started on day 5. The height of grass increased with increasing time and the maximum standard deviation of height measurement was 9%. The height of ryegrass was considerably lower with the C3 composition in which 100% sediments were used. The height of ryegrass was at the maximum with 100% potting soil having the C1 composition. A higher increase in the height of ryegrass in the C1 mixture was because industrial soils are expressly fabricated to improve the soil quality as they are rich in nutrients and organic matter and have higher conductivity. Therefore, 100% sediments had low growth in comparison with the C1 mixture. The addition of sediments in potting soil improved the performance of the mixture, as ryegrass height and seed germination were nearly similar in the mixtures C1 and C2. This observation shows that agronomic and saline soils (topsoil layer) can be replaced with dredged sediments to improve the quality of soils and increase crop yield.

Ryegrass height was reduced to 5 cm when it surpassed the threshold of 10 cm at different time intervals. The mass of fresh ryegrass biomass was measured to observe the variation in biomass production with different compositions. Table 7 shows the yield of biomass of ryegrass for several ryegrass cuttings with different compositions at various time intervals.

Table 7. Ryegrass biomass yield at different cuttings and final height.

Yield of Ryegrass (g)								
Cutting	1	2	3	4	5	6	7	8
Composition C1	8.27	9.34	10.6	11.24	38.4	24.3	11.72	34.41
Composition C2	6.25	9.75	7.85	9.83	27.83	21.06	8.79	26.3
Composition C3	3.49	5.06	6.88	-	-	-	-	-
The final height of ryegrass and biomass yield								
Composition	Mass (g)	Average height (cm)					Yield (kg/m ²)	
Composition C1	34.41	11.5 ± 0.5					0.25 ± 0.018	
Composition C2	26.3	11.5 ± 0.5					0.18 ± 0.014	
Composition C3	6.88	7.5 ± 0.5					0.05 ± 0.006	

Table 7 shows that the yield of ryegrass was maximum with the composition C1. The yield of biomass of ryegrass with 100% potting soil (C1) and 50% potting soil + 50% sediments (C2) was considerably higher than the biomass yield with 100% sediments (C3). This trend is similar to the height variation of ryegrass shown in Table 6. Kiani et al. (2021) [25] investigated the biomass yield of ryegrass by using dredged sediments. Its value was around 0.5 kg/m² after 63 days and 2.88 kg/m² after 243 days. Ryegrass yield with Usumacinta sediment compositions C1, C2, and C3 was 0.25, 0.18, and 0.05 kg/m² at 66 days. The lower yield with Usumacinta River sediments compositions is because ryegrass in the present study was cut every 2 to 3 days when it reached 10 cm in length, while Table 7 shows the final ryegrass yield after cutting at 66 days. Additionally, the type of sediments, watering, and plant seeds change the growth of plants significantly.

Agronomic recovery of dredged sediments has some drawbacks as the presence of contaminants in dredged sediments can lead to serious ecological challenges and health problems [4]. Sediments have a heterogeneous nature; therefore, recovery of sediments needs extensive characterization before their reuse in agronomy and landscaping applications. In addition, mixing higher volumes of sediments with agronomic soils may adversely affect soil structure if sediments and existing soils are not compatible.

4. Conclusions

In this study, the agronomic characteristics of Usumacinta River sediments were examined for their reuse in agronomy and landscaping. The physicochemical and mineralogical properties of Usumacinta River sediments are similar to those of agricultural soils. These sediments have an alkaline nature with a pH value of 8.5. The percentage of fine particles (clay) in sediments is around 13%. The organic matter of sediments is low and its value is 5.7%. Usumacinta sediments have a nonsaline nature, as their electrical conductivity and sodium absorption values are considerably low. Environmental parameters of sediments indicate that heavy metals and organic contaminants are below the prescribed limits.

Sediment characterization was followed by the cultivation of ryegrass by mixing soil with potting soil. Three soil–sediment compositions were tested in the greenhouse at a temperature of 30 °C and relative humidity of 70 °C. Germination of ryegrass was alike in all mixtures but the growth of grass was sustainably lower with 100% sediments. The 50% potting soil replacement with sediments demonstrated comparable growth with 100% potting soil. Additionally, the germination of ryegrass was similar in all three mixtures. Growth and germination of ryegrass with different sediments and soil compositions highlight the prospect of sediments to partially replace commercial soils. They have the potential to improve the quality of soil and minimize the use of commercial fertilizers, as the sediments are rich in nutrients such as potassium, iron, etc. Experimental results on ryegrass seem promising for the use of sediments as a sustainable resource in agronomy and landscaping.

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References

1. AFNOR NF EN ISO 11885; Water Quality—Determination of Selected Elements by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Association Française de Normalisation: Paris, France, 2016.
2. AFNOR NF ISO 10390; Qualité du Sol—Détermination du pH. Association Française de Normalisation: Paris, France, 2016.
3. AFNOR NF ISO 11265; Qualité du Sol—Détermination de la Conductivité Électrique Spécifique. Association Française de Normalisation: Paris, France, 2016.
4. AFNOR NF P 94-048; Sols: Reconnaissance et Essais. Détermination de la Teneur en Carbonate. Méthode du Calcimètre. Association Française de Normalisation: Paris, France, 2016.
5. AFNOR NF P 94-068; Sols Reconnaissance Et Essais—Mesure de la Capacité D’adsorption de Bleu de Méthylène d’un sol ou d’un Matériau Rocheux—Détermination de la Valeur de Bleu de Méthylène d’un sol ou d’un Matériau Rocheux par L’essai à la tâche. Association Française de Normalisation: Paris, France, 2016.
6. AFNOR NF X31-107; Qualité du Sol—Détermination de la Distribution Granulométrique des Particules du Sol—Méthode à la Pipette. Association Française de Normalisation: Paris, France, 2016.
7. AFNOR XP P94-011; Sols: Reconnaissance et Essais, Description—Identification—Dénomination des Sols. Terminologie—Éléments de Classification. Association Française de Normalisation: Paris, France, 2016.
8. AFNOR XP P94-047; Sols: Reconnaissance et Essais—Détermination de la Teneur Pondérale en Matières Organiques d’un Matériau—Méthode par Calcination. Association Française de Normalisation: Paris, France, 2016.
9. AFNOR XP X33-012; Caractérisation des Boues—Dosage des Hydrocarbures Aromatiques Polycycliques (HAP) et des Polychlorobiphényles (PCB). Association Française de Normalisation: Paris, France, 2016.
10. SEDIBRIC. *Valorisation de Sédiments en Briques et Tuiles. Transition Ecologique et Valorisation Economique*; Les Assises du Port du Futur: Paris, France, 2018. Available online: https://www.portdufutur.fr/sites/portdufutur/files/fichiers/2019/02/SEDIBRIC_bourdin.pdf (accessed on 16 October 2023).
11. Anger, B. Caractérisation des Sédiments Fins des Retenues Hydroélectriques en Vue D’une Orientation Vers des Filières de Valorisation Matière. Ph.D. Thesis, Université de Caen Normandie, Caen, France, 2014; p. 302. Available online: <https://hal-normandie-univ.archives-ouvertes.fr/tel-01938082> (accessed on 16 October 2023).
12. Arnot, R. The effect of seed weight and depth of sowing on the emergence and early seedling growth of perennial ryegrass (*Lolium perenne*). *J. Br. Grassl. Soc.* **1969**, *24*, 104–110. [CrossRef]
13. Baran, A.; Tarnawski, M.; Koniarz, T.; Jasiewicz, C. Agricultural use of sediments from narożniki reservoir—Yield and concentration of macronutrients and trace elements in the plant. *Infrastruct. Ecol. Rural Areas* **2016**, *4*, 1217–1228. [CrossRef]
14. Bénédicte, D. La Faisabilité de la Valorisation des Sédiments de Dragage de L’estuaire de la Vilaine, une Démarche Territoriale. Master’s Thesis, Ecole des Métiers de l’Environnement, Institution d’Aménagement de la Vilaine, Vilaine, France, 2017. Available online: https://www.eaux-et-vilaine.bzh/_BDU/20171221134553_Rapport-Valorisation-Vases-2017_VF.pdf (accessed on 16 October 2023).
15. Brigham, R.D.; Pelini, S.; Xu, Z.; Vázquez-Ortega, A. Assessing the effects of lake-dredged sediments on soil health: Agricultural and environmental implications for northwestern Ohio. *J. Environ. Qual.* **2021**, *50*, 494–503. [CrossRef] [PubMed]
16. Canet, R.; Chaves, C.; Pomares, F.; Albiach, R. Agricultural use of sediments from the Albufera Lake (eastern Spain). *Agric. Ecosyst. Environ.* **2003**, *95*, 29–36. [CrossRef]
17. Del Negro, R. Characterization of Usumacinta River’s Sediments. Master’s Thesis, Université de Nantes-IFSTTAR Nantes, Univ Lyon-INSA Lyon, Nantes, France, 2019; 18p.
18. EC (European Commission); van Beek, C.; Toth, G. *Risk Assessment Methodologies of Soil Threats in Europe—Status and Options for Harmonization for Risks by Erosion, Compaction, Salinization, Organic Matter Decline and Landslides*; JRC Scientific and Policy Reports, EUR 24097 EN; European Commission: Brussels, Belgium, 2012; 84p.
19. Fonseca, R.M.; Barriga, F.J.; Conceicao, P.I. Clay minerals in sediments of Portuguese reservoirs and their significance as weathering products from over-eroded soils: A comparative study of the Maranhão, Monte Novo and Divor Reservoirs (South Portugal). *Int. J. Earth Sci. (Geol. Rundsch.)* **2010**, *99*, 1899–1916. [CrossRef]
20. Fourvel, G. Valorisation Agronomique des Sédiments Fins de Retenues Hydroélectriques en Construction D’anthroposols Fertiles. Ph.D. Thesis, Agrocampus Ouest, Rennes, France, 2018; 397p. Available online: <https://tel.archives-ouvertes.fr/tel-02136422> (accessed on 16 October 2023).
21. GTR. *Réalisation des Remblais et des Couches de Forme, les Principes Généraux et les Annexes Techniques*, 2nd ed.; Guide Technique; CEREMA: Bron, France, 2000; 211p, ISBN 211085707-2.
22. Guihéneuf, S. *Valorisation de Déchets et de Co-Produits bio et Géo-Sourcés Dans la Formulation de Matériaux De Construction en Terre Crue*; Batylab Conference Presentation: Rennes, France, 2023. Available online: <https://www.batylab.bzh/wp-content/uploads/simon-guiheuneuf-valorisation-de-dechets-et-de-co-produits-bio-et-geo-sources.pdf> (accessed on 16 October 2023).

23. GNIS. Cultivons la Diversité des Plantes Cultivées, Ryegrass Anglais. Techniques de Culture et Activités Pédagogiques, France. 2008. Available online: https://www.semencemag.fr/images/fiches_bo/cultiver-jardiner-ray-grass-anglais.pdf (accessed on 16 October 2023).
24. Javaid, M.M.; Mahmood, A.; Alshaya, D.S.; AlKahtani, M.D.F.; Waheed, H.; Wasaya, A.; Khan, S.A.; Naqve, M.; Haider, I.; Shahid, M.A.; et al. Influence of environmental factors on seed germination and seedling characteristics of perennial ryegrass (*Lolium perenne* L.). *Sci. Rep.* **2022**, *12*, 9522. [CrossRef] [PubMed]
25. Kiani, K.; Raave, H.; Simojoki, A.; Tammearg, O.; Tammearg, P. Recycling lake sediment to agriculture: Effects on plant growth, nutrient availability, and leaching. *Sci. Total Environ.* **2021**, *753*, 141984. [CrossRef] [PubMed]
26. Kotuby-Amacher, J.; Koenig, R.; Kitchen, B. Salinity and Plant Tolerance. Utah State University Extension 2000, AG-SO-03, 8p. Available online: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1042&context=extension_histall (accessed on 16 October 2023).
27. Lembke, W.D.; Mitchell, J.K. Dewatering dredged sediment for agriculture: Lake Paradise, Mattoon, Illinois. *Trans. ASAE* **1983**, *26*, 0805–0808. [CrossRef]
28. Michallet, I.; Charruau, P.; Monzón Alvarado, C. (Eds.) *Les Sédiments du Bassin Versant de l'Usumacinta en 12 Questions*; GRAIE: Lyon, France; ECOSUR Mexique: Chiapas, Mexico, 2022; 49p, ISBN 978-2-917199-11-49782917199114.
29. Macía, P.; Fernández-Costas, C.; Rodríguez, E.; Sierpc, P.; Pazos, M.; Sanromána, M.A. Technosols as a novel valorization strategy for an ecological management of dredged marine sediments. *Ecol. Eng.* **2014**, *67*, 182–189. [CrossRef]
30. Martínez-Nicolás, J.J.; Legua, P.; Núñez-Gómez, D.; Martínez-Font, R.; Hernández, F.; Giordani, E.; Melgarejo, P. Potential of dredged bioremediated marine sediment for strawberry cultivation. *Sci. Rep.* **2020**, *10*, 19878. [CrossRef] [PubMed]
31. McManus, J. Grain size distribution and interpretation. In *Techniques in Sedimentology*; Tucker, M.E., Ed.; Blackwell Scientific Publications Ltd.: Chichester, UK, 1988; pp. 63–85. ISBN 0-632-01372-9.
32. MEDD. *Gestion des Sédiments Extraits de Cours D'eau et des Canaux*; Direction de L'eau et Direction de la Prévention des Pollutions et des Risques. Ministère de l'Ecologie et du Développement Durable: Paris, France, 2020.
33. Nikafkar, N.; Alroaia, Y.V.; Heydariyeh, S.A.; Schleiss, A.J. Economic and commercial analysis of reusing dam reservoir sediments. *Ecol. Econ.* **2023**, *204*, 107668. [CrossRef]
34. Renella, G. Recycling and Reuse of Sediments in Agriculture: Where Is the Problem? *Sustainability* **2021**, *13*, 1648. [CrossRef]
35. Safhi, A.M. Valorisation des Sédiments de Dragages dans des Bétons Autoplaçants: Optimisation de la Formulation et Étude de la Durabilité. Ph.D. Thesis, Ecole Nationale Supérieure Mines-Télécom Lille Douai, Université de Sherbrooke, Québec, QC, Canada, 2020. Available online: <https://theses.hal.science/tel-03161520> (accessed on 16 October 2023).
36. Sheehan, C.; Harrington, J.; Murphy, J.D. Dredging and Dredged Material Beneficial Reuse in Ireland. *Terra et Aqua* 2009, Number 115. Available online: <https://sword.cit.ie/cgi/viewcontent.cgi?article=1031&context=dptcivstengart> (accessed on 16 October 2023).
37. Sun, C.; Feng, D.; Yu, C.; Sun, J.; Han, X.; Zhang, M.; Zhang, P.; Han, H.; Mao, W.; Shen, X. The dynamics characteristics of soil water infiltration and capillary rise for saline-sodic soil mixed with sediment. *Water* **2022**, *14*, 481. [CrossRef]
38. UNPG. *Granulats: Parution des Chiffres clés 2019*; L'industrie Française des Granulats: Paris, France, 2021. Available online: <https://www.unicem.fr/wp-content/uploads/2021/12/unpg-chiffres-2019-web.pdf> (accessed on 16 October 2023).
39. USDA-NRCS. *Guide to Texture by Feel*. U.S. Department of Agriculture, National Resources and Conservation Service, USA; 1999. Available online: www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054311 (accessed on 16 October 2023).
40. USSLS. Diagnosis and Improvement of Saline and Alkali Soils. In *Agriculture Handbook*; Richards, L.A., Ed.; n°60; United States Salinity Laboratory Staff, Department of Agriculture: Washington, DC, USA, 1954; 166p.
41. Urbaniak, M.; Lee, S.; Takazawa, M.; Mierzejewska, E.; Baran, A.; Kannan, K. Effects of soil amendment with PCB-contaminated sediment on the growth of two cucurbit species. *Environ. Sci.* **2020**, *27*, 8872–8884. [CrossRef] [PubMed]
42. Westerberg, V. Meeting the demands of the construction industry—The economic case for re-using sediment from the Tuyamuyun Hydropower Complex. European Union project “Central Asia Nexus Dialogue Project: Fostering Water, Energy and Food Security Nexus and Multi-Sector Investment. 2022. Available online: <https://uploads.water-energy-food.org/resources/Cost-and-benefit-analysis-on-sediment-removal-and-recycling-at-THC.pdf> (accessed on 16 October 2023).
43. Zhou, Z.C.; Shangguan, Z.P. The effects of ryegrass roots and shoots on loess erosion under simulated rainfall. *Catena* **2007**, *70*, 350–355. [CrossRef]

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