IJESKA contribution to science
International Journal of Earth Sciences Knowledge and Applications
journal homepage: http://www.ijeska.com/index.php/ijeska

Review Article e-ISSN: 2687-5993

Dredged Sediments are One of the Valuable Resources: A Review

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INFORMATION

Article history
Received 10 March 2022
Revised 01 April 2022
Accepted 01 April 2022

Keywords
Dredged sediments
Waste recycling
Secondary raw material
Natural resources
Global sustainability

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ABSTRACT

Worldwide, the preservation of non-renewable resources and recycling waste materials in the potential applications are gaining global attention. In this context, rigorous research studies focus on finding solutions to reuse and recycle various waste materials. Among the different types of waste materials, the dredged sediments are one of the valuable resources having potential to replenish the depletion of natural resources by reusing and recycling as secondary raw material in various applications. The process of sediments dredging is an essential and routine activity for ports and harbors to maintain sustainable navigation systems in the sea and river environment; on the other hand, continuous accumulation of contaminated dredged sediment harms the environment, ecology, and marine ecosystems. Managing the dredging process and dredged sediment is a fundamentally important aspect of marine and river ecosystems. The technology development to recycle dredged sediments as secondary raw materials can supplement natural resources and it would be a viable solution to eliminate environmental pollution, alleviate the problem of land scarcity for waste dumping, and partially can meet the demand of resource gap. This article presents the state of the art of recycling and valorization opportunities of dredged sediments, which leads to replenishing the depletion of natural resources and increasing global sustainability.

1. Introduction

The dredging is a process of sediment removal from the bottom of harbors, water channels, rivers, lakes, and other water bodies. Sediment dredging is of utmost importance for ports, water and ocean transportation systems to maintain necessary depth for navigational safety, including maintenance (Bianchini et al., 2019; Vogt et al., 2018; Baver, 2015). Sedimentation is the natural process of silt and sand washing downstream, gradually fills harbors, water channels, the bottom of the rivers, and lakes; it is the product of the complex process of erosion that has disintegrated soil into different grain sizes such as sand, silt, clay including a certain amount of organic matter, and carried that material through water flows in seas and rivers gradually settle out on the bottom of the respective water bodies, it is a ubiquitous process for every water bodies (Tilai et al., 2019; Liu et al., 2019; Mekuria et al., 2020).

The disposal of dredged sediments (DSs) from the sea and river poses potential environmental hazards (Zhang et al., 2019; Ferrans et al., 2021). Sediments of water bodies belong to the critical problems in port and harbor management mainly due to the reducing capacity of water traffic movement, degradation of environment and ecology, and the colossal amount of dredged sediment (DS) is a burden for the biosphere. On the other hand, natural resources are rapidly depleting due to the linear consumption model and recently increasing interest in beneficial uses of DSs in resource optimization and reducing environmental pollution. Managing DS is a severe problem worldwide (Cappucci et al., 2019). Accumulation of an enormous amount of DS leads to negative consequences. Therefore, possible recycling of DS is to find new ways in respect of resource utilization, sustainability, profitability, and efficient use of DSs through various processes and applications that become increasingly important. The DS is a significant alternative resource worldwide accumulating in the water bodies. Worldwide it has been estimated that about 25,500 storage reservoirs exist with a total storage volume of approximately 6,464 billion cum (Mymrin et al., 2017; Norén et al., 2020). Over the globe, average annual reservoir storage losses due to sedimentation vary from 0.1-2.3%; however, the yearly average world storage loss is about 1.0% (Chaudhry, 2012). Global estimates of sediment loading to the ocean vary widely but are in the order of 15 to 20 billion tonnes per year (Walling and Webb, 1996).

Sediment dredging is very essential for ports, rivers, and water channels for safe and efficient operation and to maintain sufficient depth for maritime safety, including maintenance and environmental aspects. Therefore, millions of cubic meters of sediments materials annually are dredged from port and harbors areas, water channels, and rivers worldwide. Irrespective of the reason for dredging, once the sediments have been dredged, the same materials must be beneficially used or otherwise appropriately managed to ensure the sustainability of the ocean and river traffic transportation system and minimize potential adverse consequences to the environment, ecology, and public health.

The suitable recycling process for the dredging of sediments should be decided based on the mechanical, chemical, and physical properties. The DS may be contaminated by different sources irrespective of any location. DS is also subject to complex sediment transport regimes, causing dispersed contamination far away from the original location of sources (Mitchell, 2020). These sediments pose severe challenges for remediation and restoration programs for dredging activities. Sediment contamination usually consists of fractions of fine-grain particle sizes, which are not worthwhile for restoration into the coastal environment.

Table 1. Quantity of DS from few countries/locations

Country / Locations	Period	Description of quantity/volume of dredging sediments (Annually/ periodically)	Sources
India (all ports)	2013–2017	359.6 M m^3	Indian Infrastructure (Dredging), 2019
France, Germany, the Netherlands and United Kingdom		30–50 M m^3 each annually	Harrington et al., 2016
France		174.0 million tonnes	OSPAR, 2017
Netherlands		158.4 million tonnes	OSPAR, 2017
United Kingdom		103.2 million tonnes	OSPAR, 2017
United States		200–500 M m^3	SMED, 2018
United States	2011–2018	2.4 million m^3 annually	Mymrin et al., 2017
Bremen, Germany		600,000 m^3	Kay and Volker, 2002
Brazil		80,313,000 m^3	Brasil, 2009
Atlantic coasts		11.3 million tonnes	CETME, 2012
Mediterranean coasts		2.4 million tonnes	CETME, 2012
Sweden		1.4 M tonnes	CETME, 2012
Belgium	2008–2014	267.2 million tonnes	OSPAR 2017
Germany	2008–2014	228.7 million tonnes	OSPAR 2017
	2009	3,700,000	IBAMA, 2013; APPA, 2012; 2009
Ports of Paranagru and Antonina in Parana State	2011	110,000	IBAMA, 2013; APPA, 2012; 2009
	2013	8,000,000	IBAMA, 2013; APPA, 2012; 2009

On the other hand, sediments with fine grain particle size provide the suitable raw material for several applications and treatment options with high value and beneficial applications. Worldwide, regulatory programs often realize DS as waste, whereas in the 21st century, DS should be viewed as a global resource. The DSs are available in large quantities, and it is pretty easy to transport through waterways so that dredged materials can be used as a valuable alternative to virgin resources. The potential use of sediment materials has environmental, societal, and economic benefits, which lead an essential role in global sustainable development.

In the context of sustainable sediment management and ecological aspect, it can be said that DS should be a valuable alternative as a natural resource rather than call it a solid waste. Exploring the required mechanical, chemical, and physical properties of the DS would lead to a most appropriate option for different applications, the utilization of DS can lead to replenishing of the depletion of natural resources, reduce greenhouse gas (GHG), enhance economic development, and increase global sustainability (Balkaya, 2019; de Vincenzo et al., 2019; Yoobanpot et al., 2020; Zheng et al., 2019).

2. Global Perspective

Global trade and commerce are proliferating, and almost 80% of the trade volume is transported depends on marine transportation systems (PIANC, 2011). Management of seaport is one of the crucial challenges to manage seaborne marketing, and port managements need to consider the proper navigable depth to stay smooth operational condition (Norén et al., 2020; Pellegrini et al., 2021). The presence of anthropogenic activities throughout the globe and the ports of seas and rivers generate an enormous amount of DS (Cox et al., 2021), worldwide generation of DSs presented in the Table 1.

Worldwide most of the ports are established in deltas or the regions where huge quantities of sediment load of fine particles exist. Consequently, many ports are suffering from enormous volumes of maintenance dredging (IADC, 2015; Baptist et al., 2019). The process of dredging is the removal of sediments, including debris from the bottom of the harbors, rivers, lakes, and other large water bodies. In general, the sand and silt wash downstream, and sedimentation gradually take place as a deposited material in the bottom of channels, harbors, rivers, and lakes, which creates a critical problem for navigation systems due to lack of sufficient depth availability, as for navigation purpose to maintain the required level is utmost important, so dredging is a routine activity to remove sediment from waterways around the world.

Depending on the situation and purposes, three different types of dredging are very well-known capital, maintenance, and remediation dredging. Capital dredging is mainly one-time dredging in harbor basin areas and navigational channels to increase the required depth to receive ships, generally; in this dredging process, old and uncontaminated sediments are dredged, and its involvement with capital expenditure (Wahab et al., 2017; Martens et al., 2018). Maintenance dredging is a routine process conducted mainly to remove sediments from navigation channels, moorings, and berths to maintain safe depth for navigation and other related purposes (Ahadi et al., 2018; Ghaly et al., 2019). Remediation dredging or environmental dredging helps comply with ecological standards for removing dangerous contaminants sediments. Ultimately, this process aims to enhance the overall quality of water bodies and restore the marine and aquatic ecosystems (Fan et al., 2019; Kvasnicka et al., 2019; Liu et al., 2015).

A recent trend on preserving natural resources, recycling and reuse of waste, is gaining increasing attention in resource optimizations and sustainable development. Dedicated research studies from institutes (Research and Development Centre) have been conducted to find solutions to innovate environmentally friendly products and materials. Nowadays, the sediments materials from sea, river, channel, and lake have been representing a way to preserve non-renewable resources by recycling and reusing DSs as secondary raw material in different applications such as backfilling, embankment, concrete, roads, and other many relevant utilizations (Miraoui et al., 2012; Onorati et al., 2013; Lirer et al., 2017; Wang et al., 2018; Baptist et al., 2019; Slimanou et al., 2020).

Table 2. Chemical compositions of the dredged sediments

Chemical composition (%)	Aouad et al., 2012	Mymrin et al., 2017	Slimanou et al., 2019	Yoobanpot et al., 2020	Slimanou et al., 2020
SiO_2	55.51	71.0	46.76	66.20	44.97
Al_2O_3	6.52	10.1	13.97	19.30	14.17
Cao	5.77	2.6	17.23	1.01	15.26
MgO	0.63	1.1	2.63	0.91	2.15
Fe_2O_3	3.29	3.8	5.3	6.67	4.86
TiO_2		0.8			0.69
SO_3		0.1	0.39	0.19	
P_2O_5		0.1			0.19
Na_2O	0.59	4.5	1.19	3.98	1.11
MnO		0.1			0.03
K_2O	1.81	3.4	2.23	3.98	2.07

3. The Disposal and Environmental Impacts of DSs

To reduce the negative environmental impact, sustainable strategies for managing DSs are becoming a crucial challenge for scientists, researchers, and management of ports and harbors, as sediments management involves the sustainable design and development of ports dock channels in a marine environment. The dredging process influence to degrading marine and coastal environment and ecological systems through various ways such as mechanical dredging process with high energy consumption and release GHG, noise produce by dredging operation reduce the foraging efficiency of marine mammals, degrading water and air quality (Bianchini et al., 2019; Bolam et al., 2006; Erftemeijer et al., 2012; Manap et al., 2015). Sedimentation of marine and sea environments in a few specific locations is considered as the main stressor for coral species and their habitats. In most of cases, dredging operation damages habitats of coral reefs, it may be directly or indirectly, sediment deposited on the reefs surface area can smother corals and interfere with their biological process, but their existence in risk and causing mass-scale bleaching events, nutrient pollution, disease outbreaks and overfishing (Babcock et al., 2002; Storlazzi et al., 2015; Birrell et al., 2005; Erftemeijer et al., 2012).

4. Chemical Compositions of DSs

The potential uses of DSs for various applications would be possible only after examining the materials' characteristics. Several studies have determined the chemical composition of DSs in the different locations; few of them are presented in the Table 2.

5. The Beneficial Use of DSs for Various Applications

With rapid urbanization and infrastructure development, waste generation increases faster; subsequently, managing waste with proper disposal facilities became a crucial challenge. Due to a shortage of land, the cost of waste dumping gradually increases. Unmanaged dumping of DSs leads to damage to environmental and ecological systems. Various research studies have proven that recycling and reusing DS has a significant environmental and economic benefit and plays an essential role in global sustainability. Using DSs through the recycling process is a sustainable approach towards supplementing natural resources, reducing pollution and GHGs, energy optimization, enhancing economic development, improve sustainability on marine ecosystems. Potential applications of DSs have presented in Table 3.

6. Economic Approach Towards Recycling DSs for Sustainable Development

Globally, managing sediments from dredging operation have been a crucial challenge for all port, harbors, and river (Bianchini et al., 2019). A traditional method of off-site marine disposal of DS incurs substantial implications of economic and social cost and secondary global environmental pollution risk (Manap and Voulvoulis, 2015; Manap and Voulvoulis, 2016; Bianchini et al., 2019; Norén et al., 2020). Various research studies developed process technology to recycled contaminated DS into construction materials to be used as backfilling, embankment, brick & paver block, geopolymer materials and others relevant applications, and it seems that there is the potential of value proposition and economic viability of the products (Wang et al., 2018; Siham et al., 2008; Mymrin et al., 2017).

The development of technology to produce valuable materials from contaminated DSs offers an opportunity to use it as an alternative to virgin resources that could save energy and optimize resource efficiency resource utilization, reduce emissions and potentially contribute to a circular economy. The choice of recycling option for DS is essential in economic, environmental, sustainability terms and the perspective of the circular economy. In the future, recycling DSs may become more profitable as technologies are improved due to the shortage of virgin resources and the possible increased price of virgin materials (Norén et al., 2020; Peruzzi et al., 2020). Research has proven that many potential valorizations options exist in the DSs, .and the supply side of the DSs does not have any particular barriers to stimulate the development of the market for products developed through the utilization of dredged sediments.

However, rising demand in the market seems to lag. The real valorization of DSs is still very limited (Cappuyns et al., 2015). Relevant policies are needed to recycle DSs into a secondary raw material, thus implementing the circular economy concept (Rakshith and Singh, 2017; Peruzzi et al., 2020). Many countries have taken the initiative, and they are working mutually and cooperatively on market drivers for the beneficial and efficient use of dredged sediments. This collaboration creates economic values and sound technical knowledge for future business models regarding the efficient use of DS, leading to sustainable resources (Blažauskas et al., 2015; Bagarani et al., 2020; Carpenter et al., 2018).

Table 3. Potential use of DSs in various applications

Applications of DSs	References
Coarse and fine-grained materials	Mir et al., 2011; Deibel et al., 2007
Construction and infrastructure development	EPA, 2007; Deibel et al., 2007
Agriculture, forestry, horticulture, and aquaculture	EPA, 2007; Mir et al., 2011; Deibel et al., 2007
Concrete, aggregates, asphalt, bricks, cement, blocks, tiles and ceramics	Kamali et al., 2008; Dubois et al., 2009; Limeira et al., 2012; Reine et al., 2013; Marmin et al., 2014a; Said et al., 2015
Highway and railway embankment	Achour et al., 2014; Tribout et al., 2011; Sheehan and et Harrington, 2012
Geotechnical applications	Grubb et al., 2006; Chiu et al, 2008
Beach nourishment	Bagarani et al., 2020; De Vincenzo et al., 2019
Coastal Land Management	Marmin et al., 2014b; Ulibarri et al., 2020
Dams and embankments	Abidi et al., 2021; Houlihan et al., 2021
Biomining projects	Balkaya, 2019
Liner, gas vent, leachate drain	Çevikbilen et al., 2020

7. Zero Waste Concepts for the Industry Through Circular Economic Policy

The dredging process generates a large volume of DSs annually. The DSs can be converted into value-added products with less effort and resources. The circular model of DSs can compensate for all resources, energy, and GHG through the circular economy route; a clear policy framework and regulation can increase the rate of utilization of DSs.

While forming the policy, framework, and rules for enhancing the utilization facilities of DSs, the following barriers need to be considered.

- ✓ Lack of initiative between government and private agency for processing DS to a valuable resource/ product.
- ✓ Lack of proper policy framework/amendment of existing policies/formation of the new approach to deal with DS.
- ✓ Bridging the gap between industry and government.
- ✓ Government should make policy regarding sustainability context in respect of DS utilization.
- ✓ To make realize that DS is wealth.
- ✓ Policy formation for circular economy instead of the linear economy
- ✓ Lack of adequate and attractive scheme for the entrepreneur who can open up the startup for utilization of DS.
- ✓ Policy and government Intervention should be in the context as scheme of incentives, tax exemption, credit facilities, and flexible licensing system towards managing DS.
- ✓ Dedicated data bank hub necessary for accountability of natural resources in the country such as analysis demand and supply in constructions, Infrastructure sector, and other areas
- ✓ Policy correlation within DS utilization, sustainable development, and mitigate of climate change

8. Recommendation on the Policy Framework

The future policy options available with the policymakers for managing DSs are to promote necessary schemes and facilities within the framework of policy and regulation by different nationals with the alliance of industry partners. Few issues in managing DSs causing barrier, which needs to be addressed at the earliest to promote sustainable development through the Managing of dredged sediments, are as follows.

- ✓ Facilities for transportation of enormous amount of sediments
- ✓ Flexible licensing systems to process dredged sediments
- ✓ Safely policy

- ✓ Insurance scheme
- ✓ Startup facilities
- ✓ Financing facilities to set up a plant
- ✓ Emerging circular economic concept
- ✓ Approach to introduce code and standard
- ✓ Policy to design life cycle assessment (LCA) to reduce sediments
- ✓ Policy for compulsory use of sediments as secondary products wherever applicable
- ✓ Policy for restricting the use of natural resources
- ✓ Policy for limiting the use of certain unsustainable methods or technology to specific industries
- ✓ The particular policy required for penalties wherever applicable

9. Difficulty or Bottleneck Preventing Bulk Usage of DSs

Among the literature, roadblocks were categorized under new value chains, technological, environmental, institutional, and economic and knowledge bottlenecks (Cezarino et al., 2019). The specific needs and barriers need to be appropriately addressed to speed up the transformation towards the circular economy in managing DSs.

Major Bottlenecks towards managing bulk usage of the DSs are as follows.

- ✓ Unfavorable market forces
- ✓ Legal/policy/governance challenges at the international, national and sub-national levels
- ✓ Disposal capacity and process
- ✓ There is no strict law and regulation for preventing landfilling by DSs
- ✓ Critical barrier on transporting of DSs to a different location regarding cost, safety, environmental issues, etc.
- ✓ Major investments
- ✓ Lack of government initiative in respect of promoting mission zero waste
- ✓ Delay in necessary approval and responses from the government official pertaining to dealing of DSs
- ✓ Lack of policy frameworks, especially in the context of managing DSs
- ✓ Transparency of information systems among the government and industry partner
- ✓ Introduce code and standards on the secondary product from DSs so that users can use the products.

10. Ease in Implementing Policies

The large volume of DSs produced annually has led to various subordinate policies and legislations for controlling disposal and dealing with generated DSs would be made under law and regulation under a single umbrella. Specific forms of waste like DSs would be the subject of separate policy, principles, and rules and require different compliances, mainly are the operation, authorizations, maintenance, adequate disposal mechanisms, processing type, etc. Easy policy means it should be such that the policy should encourage utilization of DSs to produce other materials and resources.

A successful national policy can be measured by how well it manages the challenges the problem of the enormous amount of DSs and delivers the benefits from the opportunities in respect of waste to wealth, increase sustainability, enhance economic benefit.

11. Ways to Streamline Policy Implementation

The future policy options available with the policymakers for managing DSs are to promote necessary schemes and facilities within the framework of policies and regulations with the alliance of industry partners and research and development experts. Government should ensure that the proposal of policies and regulations should not conflict with societal, cultural, economic, environmental, and other potential issues. It's better to find out about the potential pros and cons of the proposed policy draft before we proceed forward with the proposed policies so that Government should not backtrack later. Before implementing a new approach, rules, and regulations, it would be worthwhile to evaluate its options.

12. Conclusion

Achieving a sustainable balance between the well-managed waterways, meeting ecosystem and environmental objectives will depend on mutual understanding between stakeholders, relevant policy coordination, and constructive transboundary cooperation. A sustainable approach towards managing DSs requires a change of view rather than a waste; dredged materials need to be seen as valuable resources. Perception issues remain crucial challenges to those promoting sustainable sediments management through the dredging process and activities. National level support will be necessary for helping to change attitudes and to promote sustainable DSs management within the existing policy framework or introducing a new policy to succeed the mission. Dredging and disposal of dredged material may negatively impact the environment and ecology in the marine and river environment. The ultimate aim of management for any research group or project should be to achieve a sustainable solution for the betterment of the planet earth; it may be directly or indirectly. An effective and favorable policy would be accomplished to achieve the sustainable utilization of DS for different applications and valuable products. In order to conserve natural resources, the use of DSs for various applications is the best alternative; we can get rid of the critical environmental hazards, can reduce the damaging effects of marine and river ecological systems, replenish the depletion of natural resources and enhance economic values through the process. It may be expected that sediment management may change in the future due to the risks posed by climate change. In the end, the design of advanced mitigation measures may reduce the contribution of GHG would be produced through dredging activities.

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