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An overview and assessment of the existing technological options for management and resource recovery from beach wrack and dredged sediments: An environmental and economic perspective

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ABSTRACT

The present work discusses the problems and management options of beach wrack and dredged sediments. Beach wrack and dredged sediments near the shores have affected the coastal ecosystem, badly. The piles of beach wrack residues might be a significant emitter of greenhouse gases (GHGs) and dredged sediment is a substantial source of heavy metals and other pollutants. The recovery of valuable resources such as metals and nutrients from these so-called "wastes" is a sustainable strategy to enhance the resilience of the coastal ecosystem and management. The beach wrack meadows can be a potential source for green energy production. Even the demand for biodegradable polymers can be supplied by utilizing the waste beach wracks. The residues of beach wrack species like *Posidonia oceanica, Zostera marina, Ulva* spc. and *Enhalus acorodies* can be very beneficial species in terms of economic growth. Red algae have been the most favored and efficient candidate for methane yield. In case of dredged sediment, dewatering of sediment is an essential step for successful resource extraction. Although, extraction methods are almost similar to that applied for soil treatment, which includes pretreatment, physical partitioning, washing, thermal treatment, biological extraction, and immobilization. The fractionation study can be a beneficial tool for determining the metal species present in the sediment. Immobilization techniques are successful but continuous monitoring is required. The vitrification technique is highly effective but very expensive. Thermal treatment is useful for volatile metals such as mercury (Hg), but costs are high. Biological extractions are comparatively cheap but time-consuming. Henceforth, very few extraction methods are available for sediment and required further advancement in this field.

1. Introduction

Beach is known all over the globe for their natural beauty, but they also contribute considerably to GDP, which accounts for nearly 10% of global GDP and is predicted to expand at a rate of 3.8 percent per year from 2015 to 2025. (OECD, 2016). Therefore, its management should be prioritized. Generally, seagrasses and wracks get accumulated on the shores which if unmanaged can cause serious environmental issues. Globally the coasts are severely affected by beach wrack and dumps of huge dredge sediments. Humans are also affected by beach wrack and dredged sediment, which includes landscape degradation (Sarafraz et al., 2016), the release of heavy metals (Ferrans et al., 2020). It may also negatively affects fisheries (Newman et al., 2015), and human health (Keswani et al., 2016). Balancing human health, natural resource capital and ecosystem function largely depends on effective resource recovery from coastline wastes. The maximum utilization of coastline wastes may only be achieved if suitable techniques and biological status can be properly and fully discussed.

1.1. Beach wrack as an environmental nuisance

The beach wrack is majorly composed of seagrass, which consists of roots or rhizomes, stems, and leaves (Hemminga and Duarte, 2000; Kupczyk et al., 2019). Due to wind directions/speed and wave action, tides, and aperiodic water level fluctuations, these seagrasses have been detached from their holdfast and accumulated near the shoreline (Boller and Carrington, 2006). The annual beach wrack production was estimated at around 1 kg DW m^{-2} per year, hence beach wracks are creating a highly efficient coastal ecosystem (Duarte and Chiscano, 1999; Liu

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Abbreviations

AC	Alternating current
DC	Direct current
DW	Dry weight
EC	European Commission
EDDS	Ethylenediamine-N,N′-disuccinic acid
EDTA	Ethylenediaminetetraacetic acid
GDP	Gross Domestic Product
GHGs	Green House Gases
HMs	Heavy metals
MRS	Mercury Recovery Services
NTA	Nitrilotriacetic acid
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
SPAMI	Specially Protected Areas of Mediterranean Importance
TCLP	Toxicity characteristics leaching test
TPH	Total petroleum hydrocarbons
UNEP	United Nations Environment Programme
USEPA	United States Environmental Protection Agency
VS	Volatile Solids

et al., 2019). The above-ground biomass turnover rate of beach wrack is around 2.6% of the total standing stock per day (Liu et al., 2019). Thus, this huge amount of accumulated seagrass can cause adverse effects on the coastal environment (Macreadie et al., 2017). Although decomposed and wrecked organic material of wrack maintain the biological diversity of micro- and macro-organisms of coastal seas by supplying them vital nutrients (Liu et al., 2019). But, decomposition of beach wrack produces unpleasant odors along with the production of greenhouse gas (GHG) in coastal habitats (Coupland et al., 2007; Chubarenko et al., 2020). Moreover, decomposition of beach wracks generates very unpleasant odor, which spoils the esthetic beauty of beaches and affects the tourism sector, severely (Corraini et al., 2018). Therefore, local responsible authorities or other agencies always wanted to sweep out or remove the wracks from the beaches at any cost.

1.2. *Dredged sediment as a source of contamination*

Oceans are the end route of several waterways. These water ways i.e. lakes, rivers, streams, ponds, etc. are receiving the pollutants from several sources like industrial, mining, agricultural, municipal sewage, road side pollution, and other activities. In the aquatic system, sediment has become the sink and root of these toxic pollutants. The alterations that occur in aquatic environmental conditions such as pH, temperature, salinity, etc. can cause transfer of these pollutants from sediment phase to the overlying water (Pal and Maiti 2019, 2020). Around the world, nearly 10–15% of the bottom sediments are contaminated with various pollutants (Fig. 1) (Yuchao et al., 2016). For the restoration of water bodies and maintenance of ports, sediment dredging has become an essential activity, worldwide (Ferrans et al., 2020). Every year millions of tons of dredged sediments are produced, globally (Mymrin et al., 2017). Thus, this huge amount of dredged sediment has raised a question in front of the environmental restoration agencies for its proper management, reuse, and disposal. These dredged sediments are loaded with various pollutants, therefore open ocean disposal of these sediments can damage the marine ecosystem, badly. so many of the countries have banned this practice (Cesar et al., 2014). Another option for dredged sediment disposal is landfilling but this practice has been responsible for contagious GHGs emissions and polluted leachates disposal, which can cause secondary environmental issues (Xu, 2017).

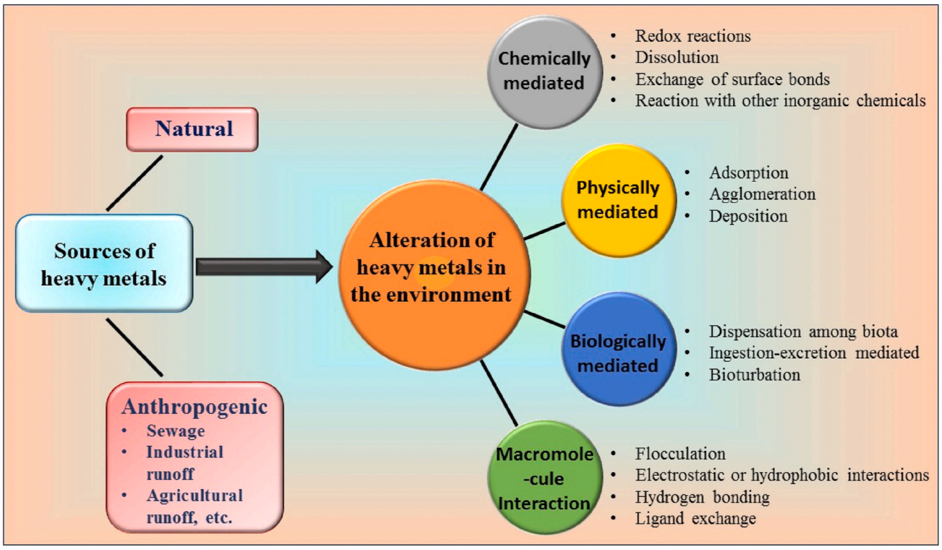

Fig. 1. Source of heavy metals and their transformation through various pathways.

1.3. *Resource recovery in the perspective of circular economy*

Despite environmental pollutants, beach wrack and dredged sediment both can be good resources of nutrients and other useful products. Nevertheless, every year about 0.3–1.0 × 10^6 t HMs deposited in sediments (Schwarzenbach et al., 2006; Costa et al., 2021), in which >99% of HMs can be accumulated in sediments (Peng et al., 2009). While, beach wracks stores a huge amount of carbon around 27.4 Tg C yr^{-1} to 50 Tg C per year (Fourqurean et al., 2012; Lima et al., 2020), along with nutrients like nitrogen (N), phosphorus (P), calcium (Ca), potassium (K), magnesium (Mg), iron (Fe), etc. (Cocozza et al., 2011). Therefore, these environmental wastes can be a good resource for secondary raw materials and economy. This provides two-way management options and promotes the circular economy. A report “Towards the Circular Economy” has brought the concept of circular economy to light (MacArthur, 2013). In the perspective of sustainable use of materials and environment, the concept of linear economy is not fit because this theory believed in “take, make, dump”. The circular economy closes the loop of linear economy in a cyclic manner by transforming renewable materials into useful products.

1.4. Previous works and present objectives

In previous studies, some methods applied for resource recovery from beach wrack and dredged sediment have been discussed, some of the topics focused on the compost production from beach wrack (Adugna, 2018; Emadodin et al., 2020); sea grasses for biocoal and anaerobic processes (Macreadie et al., 2017; Verheijen et al., 2017; Klavins et al., 2018); recovery of elements from fine fraction of waste (Burlakovs et al., 2018); technologies for remediation of metals from contaminated sediment (Peng et al., 2018); application of sequential extraction method for heavy metal speciation in soil and sediment (Okoro et al., 2012; Akcil et al., 2015a, b). Most of the studies have focused on the one or two methods suitable for resource recovery from beach wrack. Similarly, in the case of sediment, major work has contributed in the field of metal remediation and speciation of elements in sediment but none of the studies has discussed the recovery of resources from the dredged sediment. Therefore, the present review focus on the possible methods, which can use for the extraction of maximum resources from coastline wastes. The aims of the current review are i) discussion of different sustainable methods for utilizing the waste beach wrack and dredged sediment as a resource; ii) comparison of each method and its limitations; iii) and point out the obstacles and gaps occurring during their management as a baseline knowledge for future research work.

2. Beach wrack biology and its distribution

Biologically, beach wracks, majorly consists of seagrasses, which are marine flowering plants that belong to the phylum Magnoliophyta, class Alismatiflorae (Monocotyledonae), and are divided into the families: Cymodoceaceae, Hydrocharitaceae, Posidoniaceae, and Zosteraceae (Dahlgren and Bremer, 1985Dahlgren et al., 1985; Nguyen et al., 2021). This phylum includes about 67 plant species, which are generally submerged marine plants with a subterranean root, shoots, leaves, and rhizome system (Larkum et al., 2006; Boudouresque et al., 2021). The roots and rhizomes hold the plant firmly in sediment and also protect the sediment erosion during high storm events (Koch et al., 2006). In the Mediterranean Sea *Cymodocea nodosa* and *Zostera noltii* are considered pioneer species because of their rapid colonization in the bare sea floor (Borum and Greve, 2004; Sun et al., 2020). The *Zostera* spc. has a cosmopolitan distribution because they are infralittoral i.e. they can tolerate long surfacing periods (Moore and Short, 2006; Sun et al., 2020). Moreover, beach wracks are widely distributed along the coastlines of temperate and tropical regions of the world. The species diversity of beach wracks is comparatively very low (<69 species), but their distribution can be extended up to thousands of kilometers of coastline. The occurrence of beach wrack has been reported in 191 countries and six bioregions covering the tropical and temperate seas (Short et al., 2007), the details of the beach wrack distribution have been listed in Supplementary Table 1.

3. Role of beach wracks in the ecosystem

In aquatic ecosystem, beach wracks play an important role in nutrient flow and aquatic metabolism. The rapid uptake of nutrients from sediment by beach wracks and epiphytes, removes contaminants from the water column along with enhanced sedimentation activity. Beach wracks triggered the extensive growth of meadows at the interface between the water column and sediment in tidal or subtidal environments (Marbà et al., 2007). The growth of beach wrack meadows can be extended from surface top to 50 m depth in favorable physic-chemical conditions (Boudouresque et al., 2012). The upper and lower limit of beach wrack meadows can be characterized by sunlight, hydro-dynamic, and sea slopes. For instance, upper limit of beach wrack meadow has been defined as the shallowest depth covered by meadow, which is highly dependent on wave currents (Vacchi et al., 2014). On the other hand, lower limit of meadows has been recognized as the deepest depth extended by the plant that is relying upon the amount of sunlight touching the seafloor, water column transparency, and geomorphological features of that area (Ryan et al., 2007; Infantes et al., 2009). The limits of beach wrack meadows can act as a bioindicator and describe the health of the seas by indicating the hydrodynamic regimes, sedimentary balance, and influx of pollutants. For instance, a study conducted by Montefalcone et al. (2010) reported that meadows fragmentation is usually linked with relapsing aspects of the upper limit, indicating the interference of human activities. Beach wrack meadows are very sensitive to environmental changes, hence can act as bioindicators of climate change on a worldwide scale (Bhattacharya et al., 2003). To be sure, the protection of beach wrack meadows can suggest the impactful policy to the legal authorities that can be applied for the improvement of environmental conditions (Pergent et al., 2006). Generally, beach wrack meadows continuously covered the seafloor, but meadows of some species like P. oceanica could also be found in patches of various shapes, or in linear form, which are parallel to the shoreline (Borg et al., 2005; Boudouresque et al., 2012).

The ability of beach wrack meadows to renovate the abiotic components of aquatic environment made them aquatic ecosystem engineers. Moreover, the crown of beach wrack meadows helps in maintaining the coastline biodiversity by increasing the abundance of marobenthic organisms and organisms (Brun et al., 2009). Beach wrack meadows also stabilizing the sediment physico-chemical properties by altering its physiognomies (Gacia and Duarte, 2001; Boudouresque et al., 2012). The physico-chemical features of bottom sediment play a crucial role in beach wrack meadow development; especially in carbon storage (Ryan et al., 2007; Dahl et al., 2016). The beach wrack meadows are an excellent pool of carbon storage, about 10% of the annual organic carbon is sequestered in the ocean alone, using meadows and other organisms and can be embedded inside for a long period (Duarte et al., 2005; Lo Iacono et al., 2008). Beach wrack meadows can sequestrate carbon 35 times more than tropical rainforests (McLeod et al., 2011). Most of the sequestered carbon has been stored in the roots and rhizomes of meadows with relatively very small amounts of nitrogen (N) and phosphorus (P), thus the rate of decomposition of bacterial community has become very slow, which provides good storage for organic carbon in beach wrack meadows that can last up to thousands of years (Fourqurean and Schrlau, 2003; Macreadie et al., 2014).

Another important service of beach wrack meadows to the aquatic environment is to provide food reservoir to the coastal and marine food webs, the major species that rely on this food source include shellfish, macro herbivores, finfish, turtles, etc. Additionally, canopy of beach wrack meadows aids the growth of ornamental or commercially important fish species. The photosynthetic activity carried out by meadows could provide a sufficient amount of oxygen in coastal water, which can be up to 14 L/day, even in the depth of 10 m. Beach wrack meadows play an active role in sediment stabilization by entrapping the fine particles of sediment and maintain the sedimentary balance of the beaches (Brunel and Sabatier, 2009). It also prevents the resuspension of sediment by decreasing the flow rate of water (Folkard, 2005), in this way beach wrack meadows maintained the transparency of water, and increase the light penetration even in the great depth. Beach wrack meadows facilitated the nutrient flow in coastal ecosystem and accelerate the nitrogen fixation in regional water bodies. Furthermore, meadows help in preventing the littoral erosion of shoreline by regressing the wave effect on the shoreline (Whitfield et al., 2017).

Even though beach wrack meadows provided several services to the ecosystem and balance the global food chain, but beach wrack ecosystem has become the most exploited as well as threatened ecosystem on the Earth. The global loss of beach wrack has been increased by the rate of 7% per year, which was around 0.9% in 1940s, it has been assumed that we have already lost the 29% of the areal coverage of beach wrack meadows (Waycott et al., 2009). Thus, the loss of beach wrack meadows can collapse the ecosystem balance with species loss. Therefore, the concept of circular economy can enlighten the path of sustainable environmental management and would become essential in the coming days.

4. Management of beach wrack and its reuse options

Being a terrestrial plant, beach wracks senescent (leaves shedding) their leaves annually or in the middle of year, which are transported by surfs, tides, and winds towards deep waters, or on the beaches (Boudouresque et al., 2016). The senescent leaves can deposit on the sea beaches for several weeks, thus decomposition of beach wracks has been driven by decomposers. The process of decomposition produces odor and can negatively affect the tourism sector in urban areas, even the presence of beach wrack litter can affect the health of tourist badly, which ultimately reduce the esthetic beauty of beaches (Corraini et al., 2018). Furthermore, piles of wrack can be a potential source of GHG and can emit 6 μmol CO_2 m^{-2} s^{-1} (Lavery et al., 2013; Macreadie et al., 2017; Coupland et al., 2007). Thus management of beach wrack is important in terms of economy and environment. So far, four beach wrack management practices have been applied all over the world, which includes:

On-site handling and treatment can be helpful in less crowded beaches and where beach wracks are scarce in organic matter or beaches with intense realistic value, for example, SPAMI areas, national parks, etc. (Botero et al., 2015).

The temporary removal of beach wrack stockpiles. This management practice could be unauthorized because the disposal of wrack has been taken place generally behind the dunes or in illegal plants. Again, this kind of management practice has been encouraged in the least approachable touristic beaches or on shores with limited access to visitors (De Falco et al., 2009). Furthermore, this management practice has been encouraged in beaches that are susceptible to erosion (Torres et al., 2019).

Another management practice involved the collection of wracks from the beaches, manually or by using allocated equipment and nets and buried them offshore. This management practice requires a huge amount of money and land. Additionally, for the disposal of wrack intense precaution is needed because storms and tense winds can expose it, which ultimately, reduces its effectiveness (Sun et al., 2020).

Finally, the collection of beach wrack residues from the beaches and dumped in landfills. Around the world, this management practice is regularly used, even on crowded beaches (Zielinski et al., 2019). Thus, in this practice involvement of heavy vehicles is very frequent, which can trigger alterations in coastal morphodynamic (Lima et al., 2020). Furthermore, the cleaning process not only removes the beach wrack debris but also extirpates the propagules of plants, injures the invertebrate species, and excavates a huge amount of sand from the beaches (Defeo et al., 2009). The sum of practices like beach wrack residues collection, transport, and its disposal in a landfill, has made this management technique very costly (Krelling et al., 2017).

The sustainable management of beach wrack residues is missing because these practices were unable to answer a problem linked with: cost, GHGs emission (abruptly increased after wrack decomposition), excess use of non-renewable sources for wracks transport, and loss of carbon from the beach ecosystem. Therefore, considering the theme of review, i.e. the circular economy, sustainable management practice should be encouraged.

5. Sustainable methods for beach wrack utilization

In recent years, several studies have been explored the cost-effective methods for “eco-friendly” management of beach wrack residues for beach cleansing. In the following paragraphs beach management practices have been discussed in detail:

5.1. Composting

Composting is the most primitive practice, yet widely used because compost can be used as a substrate for horticulture, agriculture, and floristic cultivation practice and even can be used as a soil conditioner in kitchen gardens. The pilot-scale studies revealed that biomass composition of beach wrack residue mixes with soil organic matter and letting to obtain a good quality compost, which can be used for food cultivation (Villares et al., 2016). This compost preparation practice includes two major steps: the removal of sand particles from plant residues and the elimination of salt. A study conducted by Cocozza et al. (2011) composted the leaves of beach wrack species *Posidonia oceanica*, and received the compost with a good amount of macro-elements (e.g. N, Ca, K, Mg, Fe, etc.) with a legally acceptable concentration of heavy metals (HMs). Additionally, the study also revealed that removal of surficial and internal salt content is only required when the restoration of wrack moisture is essential (Cocozza et al., 2011). In Europe, high-quality compost was produced using beach wrack residues, but the quantity of produced compost was <20% of parent mixture (Dec. leg. January 22, 2009). In another study, excellent quality of compost has been received from beached beach wrack residues and vegetable wastes and constructed a composting plant with a treatment capacity of 15,000 m^3/year. The C/N ratio in beach wrack was reported at 14.72, while higher C/N was reported in the case of Fucus spc. (18.46), followed by Zostera marina (16.57), and Zostera noltii (14.85) (Villares et al., 2015). Thus, beach wrack seems to be a good substrate for producing high-quality organic fertilizer containing large amounts of N, K, and micronutrients such as boron (B).

5.2. Stabilization of the dune system

This practice of beach wrack management promotes the colonization of pioneer species on dunes and successively helps in sand assemblage and accumulation. This technology benefitted the beaches affected by erosion by promoting the transportation of beach residues to coastal areas, which encourage the recreation of dune morphology. This practice requires the separation of anthropic materials like glass, aluminum, plastics, etc., manually. A study conducted by Cappucci (2018), has reported the restoration of coastal dunes by using litters of beach wrack species *P. oceanica*.

5.3. Cosmetic and pharmaceutical product development

Several studies have disclosed that beach wrack extracts have antioxidant, antidiabetic, and vasoprotective properties, which can be beneficial for a human being (Newmaster et al., 2011; Rengasamy et al., 2013; Alamgir, 2018). The beach wrack species *Thalassia hemprichii* comprises polyphenolic compounds like flavonoids, phenolic acids, which are popularly known for their antioxidant properties (Nopi et al., 2018). Furthermore, the antimicrobial compounds of beach wrack helped in the suppression of microbial growth and many studies have isolated the bioactive compounds of antibacterial, antiviral, anti-inflammatory, and anti-diabetic from beach wracks (Hua et al., 2006; Ragupathi et al., 2010).

5.4. Infrastructure related products

The beach wrack residues can be used for the production of acoustic/noise separation panels for buildings. The beach wrack litters possess the property of thermal conductivity as similar to glass wool, hence can be alternatively used for thermal insulation. Only one step is required to convert this waste into resourceful material, which is salt and sand removal, in order to protect buildings from corrosion and damage. The beach wrack residues can be used for interior decoration by processing the washed beach wrack leaves and intertwined them (Torres et al., 2019).

5.5. Nonwoven textile products

The wastes of beach wrack species like *P. oceanica* and *Zostera marina* can be a boon for nonwoven textile industries and can be utilized as a raw material. The nonwoven material production technique is an advanced version of paper-making technique, in which water slurry and fibers of beach wrack wastes are placed in a rotatory wire screen to form a web. The dewatered web is pressed between mechanical rollers, and solar dried. Although, the production of nonwoven textile from beach wrack wastes has been limited to some parts of European regions and further advancement is required in this industry (EC, 2015).

5.6. Production of bio-polymers and biosorbents

The production of biodegradable thermoplastic polymers from beach wrack wastes is a new initiative by UNEP, 2018. The polymers can be used for packaging fragile goods, pastes, and fluids. Furthermore, preparation of biosorbents like biochar, activated carbon, etc. from wastes beach wracks for the remediation of inorganic and organic pollutants from the environment has become a burning topic for research among the researchers, worldwide (Ncibi et al., 2009). The pyrolytic conversion of beach wrack wracks into potential biochar has already been examined (Sohi et al., 2010; Macredie et al., 2017). The compositional analysis indicated that biochar produced from beach wrack species like *P. australis, Z. marina*, etc. has equal or higher carbon percentage than any other hydrophytic plant's biochar (Macredie et al., 2017). The yield percentage of biochar is highly dependent on the feedstock and pyrolysis temperature. The biochar produced from *P. oceanica* beach wrack species at 500 °C temperature showed a higher yield percentage, as similar to woody biomass (Chiodo et al., 2016). The stability and alkalinity potential of beach wrack biochar is very beneficial for soils and can enhance soil fertility and crop productivity (Chiodo et al., 2016; Bhatti et al., 2020).

5.7. Syngas production

Gasification process involves the thermal conversion of biomass at high temperature range (700–1000 °C) in the presence of either air, CO_2, O, H, steam, or mixtures of these to produce a combustible gas mixture also known as syngas or synthetic gas. The syngas is a combination of H, CO_2, CH_4, carbon monoxide, and trace gases. In case of seaweeds, catalyst is required in steam gasification for the reformation of tar generated from biomass pyrolysis (Duman et al., 2014). Participation of biomass ash as a catalyst enhanced the gasification rate, which can further promote the reuse of waste ash and also reduce the production cost. The technique was highly encouraged in the case of brown algae for the improvement of syngas production (Rizkiana et al., 2014). The gasification of residues of beach wrack species like *Enhalus acorodies* and *P. oceanica* has successfully produced the syngas, and used for electricity generation. A study conducted by Conesa and Domene (2015) has suggested possible pathways for energy production from beach wrack wastes by optimizing different parameter conditions, but this work needs extended effort. Furthermore, the preparation of syngas from beach wrack residues is highly dependent on biomass weight and temperature (Deniz et al., 2015). Therefore, this process required more thorough studies for its betterment.

5.8. Biogas (methane gas) production

Around the world, several studies have reported the potential conversion of beach wrack into biomethane by utilizing the anaerobic digestion technique (Marquez et al., 2013; Ashraf et al., 2017). This is a complex microbial process, which includes many intermediate reactions for disintegration of organic fraction in to biogas. Before starting the anaerobic digestion process, pretreatment of substrate is often performed. It usually improves the decomposition rate of organic content that results into higher methane yield and more stabilised end products. In the literature, different pre-treatment techniques have been reported, such as acidic, alkaline, enzymatic, washing, maceration, hydrothermal, and thermal for the improvement of anaerobic digestion of sea grass. The selection of pre-treatment techniques is decided based on the substrate characteristics, pre-treatment mechanism, and end requirements. As can be seen in Fig. 2a and b washing and maceration have commonly been applied as method of pretreatment for methane generation using sea graas. Similar to methane, other forms of energy sources like ethanol, methanol, and biohydrogen may also require a certain degree of pretreatment for better yield. The potential of biofuel generation of different algal groups is illustrated in Fig. 3.

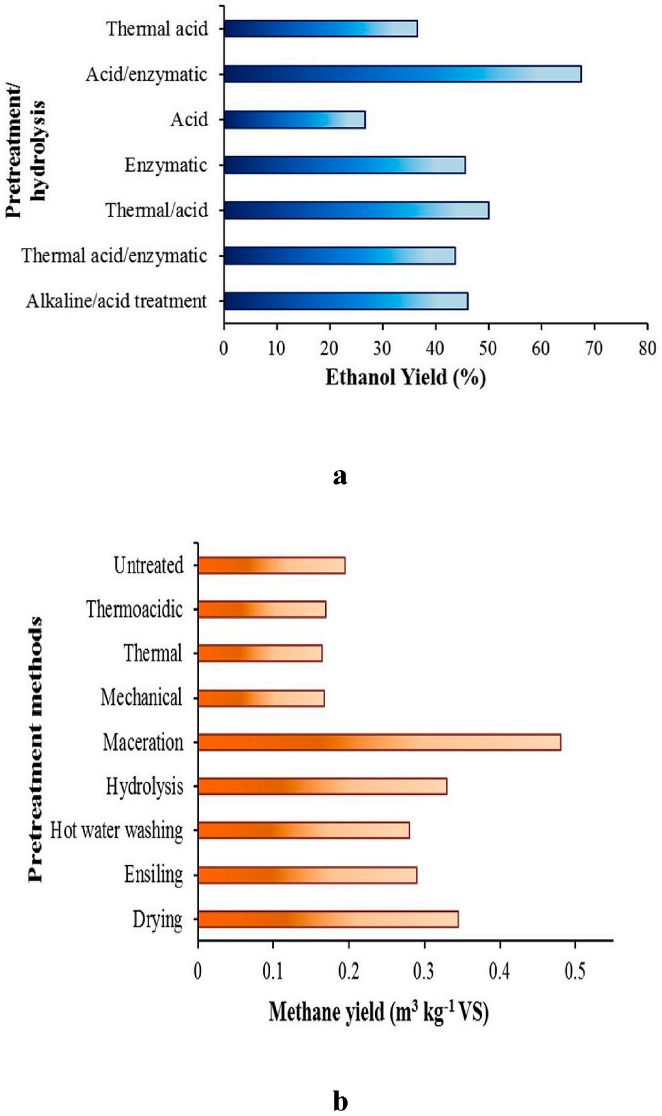

Fig. 2. (a). Effects of different pretreatment methods on methane and ethanol yield (b).

The salinity of beach wrack residues could inhibit the anaerobic digestion, therefore required a conventional activated microbial seed, which ultimately increased its costs and reduces its effectiveness (Ferrans et al., 2020). The production of biomethane from beach wrack residues the chances of harmful methane production at landfills sites and also boosted up the economic cost of waste management (Ashraf et al., 2017; Balata and Tola, 2018). About 103.1–262.3 NmL CH_4/g

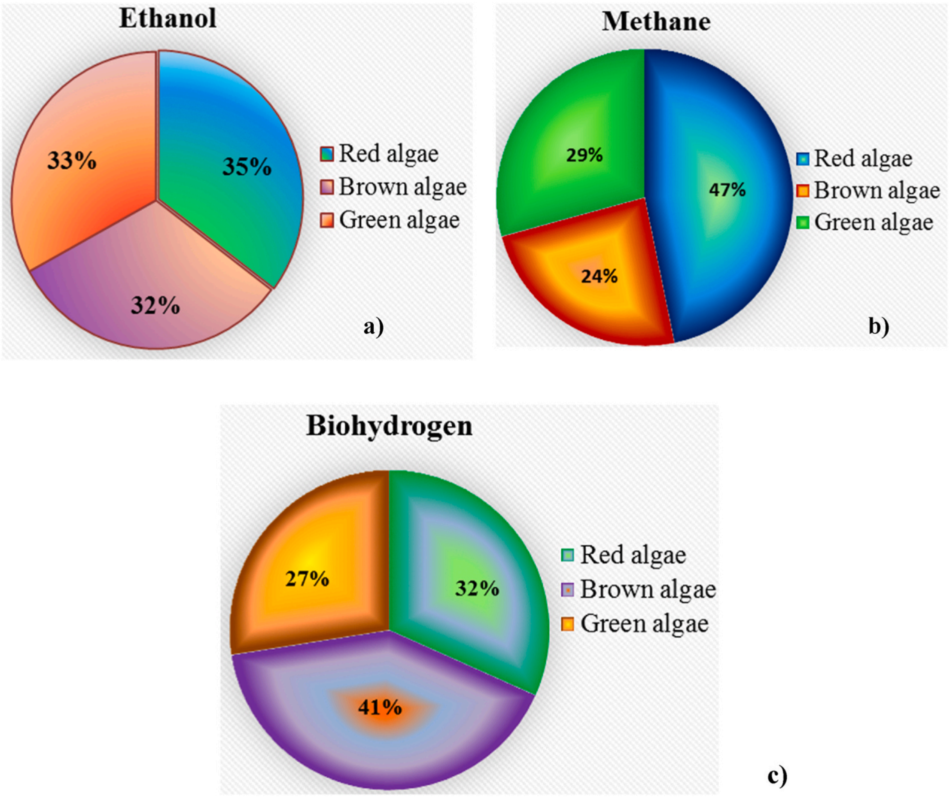

Fig. 3. Potential of different algal groups for energy sources, a) ethanol production, b) methane generation, and c) generation of biohydrogen.

methane has been produced from beach wrack and suggested that the percentage of volatile solids (VS), is highly dependent on substrate humidity and applied inoculum-to-substrate ratio (Misson et al., 2020). The details of biofuel yield extracted from different species are provided in Table 1.

Thus, provided sustainable solutions for beach wrack wastes management can improve our environmental conditions as well as closed the loop of the linear economy.

6. Sediment and dredged sediment

The soil particles with mineral and organic origin and deposited at the bed of water bodies are known as sediment (Mulligan et al., 2001). Most of the transportation of these soil particles is carried out by water, storm, ice or wind. Thus, sediments are the composition of organic and inorganic matters such as humus, algae, worms, decomposed plants, FeO, carbonates, sulfides, and interstitial water molecules. The properties of grain size distribution, density, pore water, and organic matter made the sediment heterogeneous. The smaller particle sizes of the sediment are responsible for the adsorption of contaminants on its surface because of higher surface area and organic matter loads (Fathollahzadeh et al., 2015). Nevertheless, the sulfides of sediment are also linked with the metal's association. Therefore, sediment acts as a pool for contaminants in aquatic system. Although, in recent years many of the researchers have shown their interest in sediment remediation, as compared to soil, much less is known about the sediment remediation technologies (Gilmour et al., 2013; Wu et al., 2013; Chen et al., 2017; Zang et al., 2017; Pal and Maiti 2019, 2020). Among all the available remediation technologies, sediment dredging is one of them, in which mechanical removal of the contaminated sediment has been taken place. Apart from the remediation, dredging is also necessary for navigational purposes. The drawback of this technology is that it demands a huge land for sediment disposal, therefore, characterization and contaminants analysis of dredged sediment is highly essential before transport, treatment, and disposal. Thus, this section of the review focused on the technologies available for the extraction of resources from dredged sediment, sustainably.

6.1. *Methods of resource recovery*

6.1.1. *Sequential extraction*

The sequential extraction analysis provides the information about the physico-chemical species of the elements using analytical methods (Jain, 2004). The speciation involves the partitioning of physical and chemical species of the HMs. The speciation study provides information about the potential toxicities to aquatic biota caused by different metal species. Additionally, speciation study enhances our understanding of the metal interaction chemistry of sediment and water in an aquatic environment. Thus, this technique has sought the attention of researchers in order to identify the mobility of HMs and associated risks in biota (Bourg, 1995). For separating the metal species in sediment, individual extractants are used. In the sequential extraction, strength of the applied solutions is increasing from low to high (Jain, 2004). In each extractant sediment samples are shaken for prescribed time, centrifuged and supernatant is decanted for HM analysis. After every step, sediment residue is washed thoroughly with distilled water and allow to mix the proceeding reagent and following the same procedure. In the final step, mineral acids are used to extract the HMs from the residual fraction. The concentrations of HMs extracted in each step are determined by either atomic absorption spectrophotometry or other means. To date various researchers have applied the sequential extraction techniques to sediment (Zang et al., 2017; Pal and Maiti 2019, 2020), sewage sludge (Jamali et al., 2009; Bogusz and Oleszczuk, 2018), and soils but they have observed variations in their results, which may be because of the minimum solubilization of fractions in selected extractants strength. The physical and chemical properties, such as pH, redox potential, organic, inorganic, and oxide contents of soil plays a crucial role in HMs speciation and mobility (Kabata-Pendias, 2011). Heavy metals like mercury

Table 1
Some literature survey representing the production of bioethanol from beach wracks.

S. No.	Beach wrack/ beach wrack residues	Pretreatment/ Hydrolysis methods	Ethanol concentration (g/L)	References
1.	*Alaria crassifolia*	Thermal acid/ enzymatic	25.5	Yanagisawa et al. (2011)
2.	*Gelidia dura residue after agar extraction*	Alkaline/acid treatment	2.90	Baghel et al. (2015)
3.	*Gelidium amansi*	Thermal acid/ enzymatic	18.8	Sunwoo et al. (2016)
4.	*Gelidium amansi*	Thermal/acid	22.0	Sukwong et al. (2018)
5.	*Gracilaria verrucosa*	Thermal acid/ enzymatic	19.1	Sunwoo et al. (2016)
6.	*Gracilaria verrucosa residue after agar extraction*	Enzymatic		Kumari et al. (2013)
7.	*Gelidium elegans*	Thermal acid/ enzymatic	18.4	Yanagisawa et al. (2011)
8.	*Eucheuma denticulatum*	Thermal acid/ enzymatic	13.0, 15.8	Sunwoo et al. (2016), Ra et al. (2015)
9.	*Eucheuma spinosum*	Thermal acid/ enzymatic	17.9	Ra et al. (2015)
10.	*Kappaphycus alvarezii*	Thermal acid/ enzymatic	14.5	Sunwoo et al. (2016)
11.	*Laminaria digitata*	Thermal acid/ enzymatic	3.00	Schiener et al. (2016a, b), Kostas et al. (2017)
12.	*Chaetomorpha linum*	Hydrothermal treatment Wet oxidation Steam explosion Plasma assisted treatment Ball milling	17.1, 44.0, 57.0, 64.1	Schultz-Jensen et al. (2013)
13.	*Kappaphycus alvarezii*	Thermal acid	22.5	Khambhaty et al. (2012)
14.	*Saccharina japonica*	Thermal acid, Thermal acid/ Bacillus sp., Thermal acid/ enzymatic	7.70	Jang et al. (2012)
15.	*Ulva fasciata*	Thermal/ enzyme	9.31	Trivedi et al. (2013)
16.	*Ulva pertusa*	Thermal acid/ enzymatic	18.5	Yanagisawa et al. (2011)

(Hg) and lead (Pb) have higher molecular weight organic fractions, since not affected by pH and redox potential. On the other hand, iron (Fe) is linked with both large and small molecular weight organic fraction, therefore those part linked with the smaller fraction is affected by pH only. Similarly, manganese (Mn) has a small molecular weight organic fraction, since highly portable in all pH and redox conditions. The complex and simple cations are highly mobile in the extractants, while interchangeable cations in organic and inorganic mixes have average portability, and chelated cations showed minimum mobility. The metals associated with organic or mineral lattices are only portable after decomposition and gravitated metals are mobile in solutions. The speciation of zinc (Zn), copper (Cu), cadmium (Cd), and Pb has been reported earlier (Kabata-Pendias, 2011). The metals linked with exchangeable fractions such as Cd, and Zn are weakly organically bounded and highly water soluble. The Pb is partially mobile and associated with residual fraction, whereas, Cu is majorly organically bound and exchangeable. In the case of soil, speciation is affected by added fertilizer, water, and other airborne pollutants. The sequential extraction techniques will be useful to evaluate the mobility of HMs in soil or sediment. It has been observed that Cd is highly mobile in soil and sediment, hence easily available to biota. To predict the removal efficiencies of used amendment in soil and sediment sequential extraction can be a potential indicator. The ratio of HMs extracted in exchangeable, carbonate and reducible fractions would determine the fate of selective technique or material for remediation. If the HMs percentage is found higher in exchangeable, carbonate, and reducible fractions, then it indicates the failure of used remediation technique, whereas, higher ratio of HMs in residual fraction signified the successful remediation of HMs in soil or sediment. The removal of HMs linked with organic bound and residual fractions may not be necessary because metals bounded to these fractions are chemically inert and unavailable to biota. The studies confined that HCl is not an effective extractant to extract metals from residual fraction, whereas H_2SO_4 has potential removal efficiency (Chu and Ko, 2018). The HCl can easily extract the HMs from mobile fractions, such as reducible and organic forms. Tang et al. (2017) used sequential extraction in sludge washing technique using saponin and suggested that saponin can be a good replacement for organic acids, inorganic acids, and less environmentally friendly refractory chelators in the extraction of HMs from the sewage sludge. Leermakers et al. (2019) has performed the six-step sequential extraction for the sediments of the Fe oxide rich mining deposits by adding the HCl (12 M). About 90% Zn associated with carbonate and oxide fractions, along with 70% Cu associated with organic fraction has been extracted from the sediment (Mulligan et al., 2001). In another study, about 88.14% Cd has been extracted from the biochar treated sediment (Pal and Maiti, 2019). Liu et al. (2018) extracted Cd 18–45%, and Cu, Zn, and Ni in between 5 and 15% while Pb, As, and Cr extracted less than 2% from the dredged sediment. Although various works have been noticed in the field of sequential extraction, yet more work is required in this field to be able to extract sufficient amount of metals from the dredged sediment.

Before extraction of HMs from dredged sediments certain pretreatment methods are required in order to remove the debris and dewater the dredged sediments. Usually, debris can include big concrete blocks, locomotive-automobile parts, tires, and rocks. To remove the larger particles clamshells or backhoes are generally used, while smaller particles are removed utilizing trammel or rotatory screeners (Yin et al., 2018). The dewatering methods are completely dependent upon dredging method and used technology. The dehydration of dredged sediment can be done mechanically, thermally, or electrically. The mechanical dewatering includes methods like centrifuge, gravitational settlers, belt filter presses, etc., which can successfully remove about >50% water from the sediment (Mahmoud et al., 2010). On the other hand, dewatering of dredged sediment using hydraulic methods can separate more than 20% water from the sediment. The mechanical dewatering methods are not suitable for finer sediment particles such as silt or clay (Ammami et al., 2020). The dewatering stage leads to the production of filter cake; the produced filter cake is compressed using rotary press, for additional dewatering. The rotary press technique can effectively remove the metal content from dredged sediment by about 30%, which can be disposed of in the open environment. But, dewatering process enhances the overall budget and reduces its effectiveness. Apart from rotary press, various other pilot scale and commercially available techniques are evolved, which are discussed in the following sections.

6.1.2. *Physical removal of contaminated particles*

Physical separation is very useful to eliminate finer and highly contaminated particles from the sediment. The physical separation generally includes sedimentation, vacuum extraction, centrifugation, screening, hydrocyclones, and flocculation. Hydrocyclone method is based on the solid-liquid separation, in which by applying the centrifugal force solid particles are removed from the liquid stream. Hydrocyclones can remove the particles greater than 10–20 μm size, contrary, for the removal of <50 μm size particles fluidized bed separation technique is preferred. Hydrocyclones and fluidized bed technique can be beneficial for the removal of polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and pesticides (Kim et al., 2016). Moreover, the involvement of chemicals in later stages can extract the phosphorus (P), organic and floating matters, effectively (Rulkens, 2005). For the separation of particles > 1 mm size, screening is most acceptable. The sedimentation method can be useful for the removal of contaminants having greater specific gravity. Physical treatment techniques focused on the separation of smaller particles, hence can be used as a primary treatment technique.

6.1.3. *Extraction by washing*

Extraction of HMs utilizing washing includes the involvement of extracting solution to transfer the contaminants from sediment to extracting or washing solution. Application of extracting solution can be beneficial for the extraction of metals linked with weaker bonds, such as oxides, hydroxides, and carbonates. Electro-chemical techniques can be useful for the extraction of metals like mercury (Hg), Pb, Cd, Cu, Ni, Zn, and Cr. The separation techniques like precipitation or ion-exchange can also be used for the extraction of HMs (USEPA, 2013a). But in case of metals linked with sulfide groups, the precipitation technique is not useful. For the removal of uncontaminated coarse fractions, pretreatment method can be suitable. Usage of various extractants such as acids (e.g. HNO_3, HCl, H_2SO_4), organic acids (e.g. oxalic acid, citric acid, and ascorbic acid), chelating agents (e.g. EDTA, EDDS, and NTA), or surfactants (e.g. rhamnolipids and sophorolipids) can be advantageous (Peng et al., 2018). It is essential to wash treated sediment before disposal, in order to eliminate the hazardous residuals. Although, some extractants may adversely affect the environment, for instance being an efficient extractant of HMs, EDTA has been reported as a prominent ecological environment pollutant (Bohuslavek et al., 2001; Pal and Maiti, 2019). A comparative study indicated that diluted H_2SO_4 is better than other extractants such as HCl, HNO_3, etc. for the extraction of HMs and relatively less toxic for environment (Beolchini et al., 2013). The estimated costs of sediment washing are generally ranged between 34 and 349 USD (Zhang et al., 2019). To analyse the successfulness of the applied washing technique, extraction analysis should be done at optimal conditions such as pH, type of extractant, dosage, contact time, temperature, and agitation speed. The separation company like BESCORP has extracted the Pb 65–77% from the soil by using the physical and chemical extraction methods (Dermont et al., 2008). Generally, extraction companies used the mixtures of surfactants along with oxidizing and chelating agents in extreme pressure water jets. Chemical and water washing techniques are very expensive and roughly required 40–73 USD per m^3 (Tsai et al., 2009), another important issue related to this technique is the requirement of huge land for set-up installation and unsafe for environment (Mulligan et al., 2001). Furthermore, sediment washing technique split the dredged sediment into silt-clay and sand fractions. The silt-clay and raw sediment fractions are enriched with HMs and total petroleum hydrocarbons (TPH), while sand fraction has comparatively lower value of HMs and TPH (Doni et al., 2018). Application of washing technique in fine grain sediment is a bit difficult because of their sizes, which provided a huge surface area for contaminant adsorption. In this way, these points reduce the effectiveness of washing technique. Meanwhile, involvement of microorganisms along with washing agents allowed to remove 46–56% TPH from the dredged sediment (Doni et al., 2018). Hence, the combination of microorganism (acidophilic bacterial strains) along with washing chemicals can be a very promising and cost-effective solution for material extraction from dredged sediments.

6.1.4. *Thermal extraction*

This technique is based on thermal extraction and vitrification. In this method, heat is applied for the extraction of HMs from dewatered sediment. The application of high temperature eliminates organic contaminants, whereas HMs remain in the sediment matrix. Although, extraction ability of HMs is highly dependent on the applied temperature and retention time (Mulligan et al., 2001). For instance, some metals like Hg, Cd, and As can be evaporated at <800 °C, whereas Mo and V can become leachable because of the formation of oxyanions (Akcil et al., 2015a, b; Peng et al., 2018). Organic pollutants like PHAs and other low-molecular hydrocarbons can be easily evaporated around 100–500 °C because of thermal vaporization. Whereas at >800 °C, organic pollutants are completely broken down, even some inorganic contaminants like Cd, Hg, As, etc. are evaporated or vitrified at this temperature (Mulligan et al., 2001; Zoubeir et al., 2007). Thermal extraction technique is highly encouraged for the extraction of Hg from dredged sediment because of its volatile property. Nevertheless, extraction of resources from the dredged sediment is a very tedious task because of the lack of proper instruments and moisture content of sediment. Yet, several commercially available thermal chemical extraction processes are available such as Mercury Recovery Services, X-Trax™ process, Cement Lock, and Novosol® process (Mulligan et al., 2001; Zoubeir et al., 2007; Akcil et al., 2015a, b). The Mercury Recovery Services (MRS) is a commercially available process that allowed to mix of the proprietary and Hg contaminated sediment around 150–650 °C (Mulligan et al., 2001). Mercury can be present in sulfide, chloride, or oxide form. The process is divided into two stages: dewatering of sediment and extraction of up to 99% pure Hg present in the vapor phase. The advantage of this process is no production of any secondary byproducts. The remains of the treated sediment contain < 1 ppm Hg. Although estimated costs of this process are nearly 650–1000 USD per ton (Akcil et al., 2015a, b). The X-Trax™ process can be beneficial for the extraction of organic and inorganic (especially Hg) contaminants from the soil, sludge, and sediment at low temperatures. In this process, polluted sediment is placed into a rotary dryer at 400–650 °C. The nitrogen (N) gas works as a carrier of vapors to the gas treatment chambers. Around 10–30% of Hg is extracted by dust scrubber, whereas liquid scrubber is allowed to distinct the water, Hg, sludge, and organic components from the fed. With the help of N gas Hg is condensed as pure form (Peng et al., 2018). The off-gas is purified with the help of activated carbons and particulate filters. In the Cement Lock process, dredged sediment is mixed with lime into rotary kiln reactor smelter at 1200–1600 °C temperature. The melted mixture has been quenched, and pulverized, and blended with cement mixtures. Although this technique required additional gas purifying filters (e.g. activated carbon filter and particulate filter) for the removal of volatile HMs, acid gas, other combustion byproducts from the escaped-gases. Additionally, toxicity characteristics leaching test (TCLP) is required for the HMs assessment in sediment mixed cement. The expected costs of pilot scale tests are ranged between 20 and 30 USD per m^3 (Mulligan et al., 2001). In the Novosol® process stabilization of contaminated sediment is carried out in two phases: phosphatation and calcination. The process is evolved and patented by the Solvay Company (EP1341728, 2000). The contaminated sediment is mixed with the phosphoric acid (H_3PO_4, 2–3.5%) in a tubular reactor during phosphatation process. The H_3PO_4 allowed the production of calcium phosphate minerals in the presence of calcite, which is known as a responsible factor for the extraction of HMs (Akcil et al., 2015a, b). The HMs immobilization potential of these compounds has been well noticed in soils, sewage sludge, and fly ashes (Piantone et al., 2003; Prabhakar and Samadder, 2020). While, for the calcination phase phosphate sediment is calcined at $\geqslant$650 °C in a rotary kiln, which allowed the break-down of organic matters (PAHs, pesticides, etc.) present in sediments. The phosphatation process is responsible for the end product toughness, and immobilization of metal phosphates. The estimated costs for the treatment of 1 ton raw sediments along with 50% water content is around 90.47 USD (Lafhaj et al., 2008). Additionally, for the treatment of escaped gases (carried generally H_2S, CO_2, and HMs) activated carbon and sodium bicarbonate (Na_2CO_3) is used (Aubert, 2002). In this process, two types of solid wastes are also produced: waste incinerated fly ash (20 kg/ton of sediment) and residual Na compounds (about 7–13 kg/ton of sediment) (Lafhaj et al., 2008).

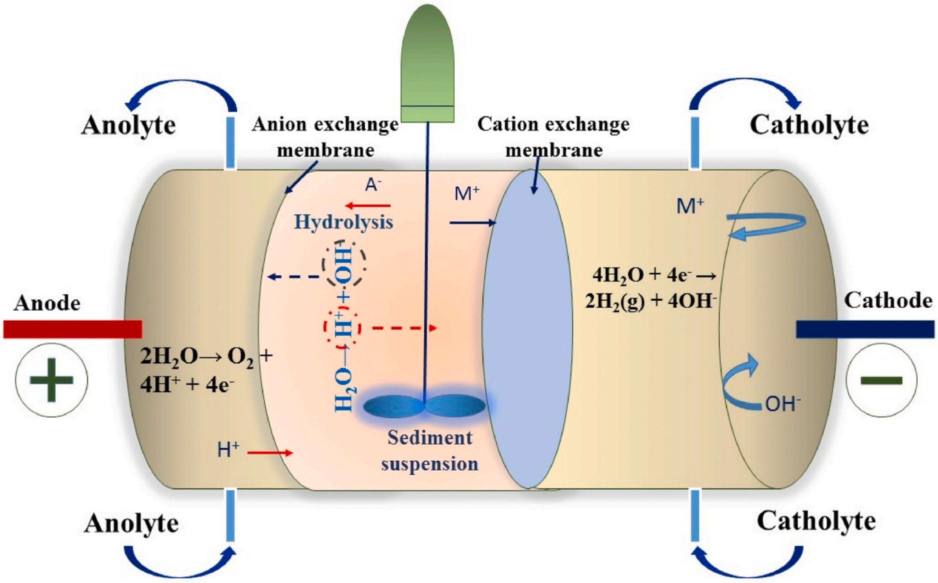

Fig. 4. Schematic diagram indicated the electrodialytic cell set-up for sediment treatment (source: Pedersen et al., 2015).

6.1.5. Electrochemical extraction

The electrokinetic extraction is also known as electrochemical extraction, the process includes the low-voltage electric current (e.g. AC or DC currents) passed between cathode and anode rods, inserted in contaminated sediment slurry (Mulligan et al., 2001; Pedersen et al., 2015). The generated electric field allowed the transfer of charged particles and metal ions towards anode or cathode, according to their charges, for instance, negatively charged particles move towards anode, while positively charged particles move towards cathode (Peng et al., 2009). After the extraction process, collected contaminants (around the electrodes) will be treated by using numerous physico-chemical procedures, such as precipitation, electroplating, ion-exchange, and other methods (Mulligan et al., 2001; Akcil et al., 2015a, b). The electrochemical treatment is most suitable for the fine-grained sediment, which adsorb maximum metal ions on its surface and not able to treat with other methods (Peng et al., 2009). Even soluble metal ions and ions that are bounded with sediment oxides, hydroxides, cyanide, nitrates, and carbonates can be easily extracted by this technique (Mulligan et al., 2001). The good side of this technique is, no or very few amounts of residues production. The basic mechanism involved in electrochemical extraction is electro-osmosis (movement of fluid), electromigration (movement of ionized chemicals), electrolysis (breakdown of ionic compounds by passing electric current), and electrophoresis (dispersion of charged particles) (Peng et al., 2009). In case of HMs extraction, electromigration technique is highly recommended because of its higher extraction efficiency (Mulligan et al., 2001). The responsible factors for HMs extraction using this method include current flow, duration, cell set-up, agitation rate, sediment properties, and dry: wet ratio of sediment. Among all these factors, extraction duration and current flow are the most determining factors (Pedersen et al., 2015). During electrode reactions hydroxyl (OH^-) and hydrogen (H^+) ions are generated at the cathode and anode, correspondingly; and when pH is disturbed these ions will migrate towards opposite poles i.e. cathode or anode as depicted in Fig. 2 (Peng et al., 2009; Pedersen et al., 2015). The pH of the sediment is determined by the available OH- and H+ ions, for instance, increased H^+ ions decrease the pH value around the anode. If the sediment slurry has acidic pH then metals ions are likely to solubilize or desorb, whereas the basic pH of sediment strikes the precipitation of metal ions in the form of hydroxides or oxyhydroxides (Pedersen et al., 2015). To enhance the extraction ability of HMs various desorbing agents like surfactants, acidification, etc. are extensively used, which solubilize the metal oxides, hydroxides, carbonates, nitrates, and other species adsorbed on the sediment surface (Peng et al., 2009). Indeed, optimization of electrochemical techniques for the extraction of HMs in soil and sediment is highly recommended along with desorbing agent advancement (Kaya and Yukselen, 2005).

6.1.6. Biological extraction

The biological extraction of HMs can be done by plants (phyto-extraction) and microbes (microbial extraction), which can partially or completely extract the target pollutants from soil, sediment, wastewater, sludge, and groundwater (Dixit et al., 2015). The phyto-extraction method can be a suitable method for contaminants extraction, land management, and soil quality improvement (Ali et al., 2013) (Fig. 3). As compared to other methods phyto-extraction method is highly efficient, eco-friendly, and economically feasible for pilot scale extraction (Ali et al., 2013). The phyto-extraction method has been extensively used for the remediation of inorganic (e.g. HMs and radioactive pollutants) as well as organic (PAHs, dyes, PCBs, etc.) from soil, sediment, water, wastewater, and sludge (Bert et al., 2009; Ali et al., 2013; Perelo, 2010; Mani and Kumar 2014; Dixit et al., 2015). The phyto-extraction technique also known as phyto-accumulation, phyto-sequestration, or phytoabsorption and highly effective for the extraction of HMs from contaminated media (Dixit et al., 2015). The process of phyto-extraction has been completed in three steps: 1) Identification and cultivation of ideal plant species at contaminated site; 2) harvesting of metal-enriched plant biomass.

From the site, and 3) post-harvesting management. Whereas, in case of dredged sediment management phytoremediation method is highly recommended because of its promising results (Doni et al., 2015; Choudhury et al., 2016). The various studies have proved that hydrophytes like *Eichhornia crassipes*, *Hydrilla* spc, etc. can efficiently uptake the HMs from contaminated sediment and also recommended the use of hydrophytes for pilot scale remediation (Xie et al., 2016; Pal and Maiti, 2019). The sediment contaminated with multiple stressors (Cu and Pb) had shown better restoration effect with *Hydrilla verticillata* rather than *Vallisneria natans* and *Ceratophyllum demersum* plant species (Xie et al., 2016). Pal and Maiti (2019) have concluded that *E. crassipes* can significantly uptake the Cd from spiked sediment slurry and stated that roots of *E. crassipes* have more metal binding ability than shoot because of rhizofiltaration process occurred on rhizosphere. Although, active transport of HMs in hydrophytes tissue is bit limited, while passive

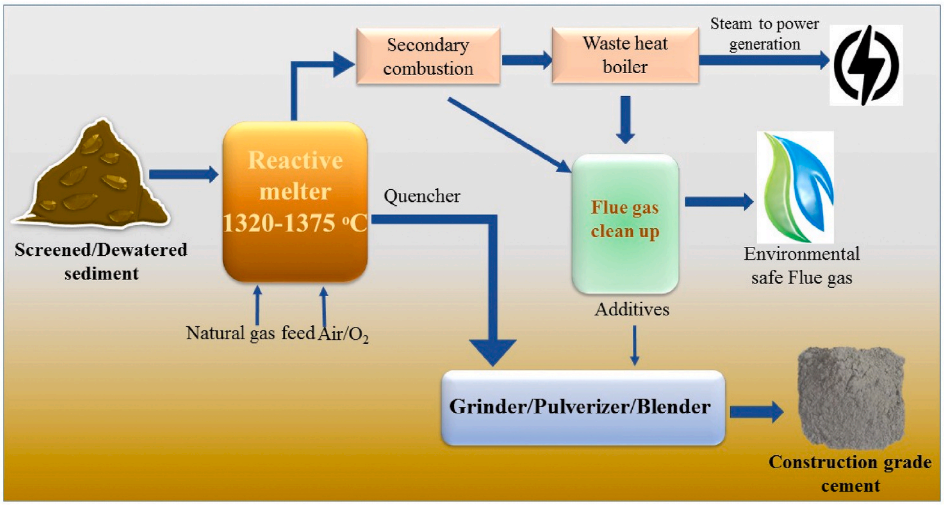

Fig. 5. Process flow diagram explained the Cement Lock process from dredged sediment.

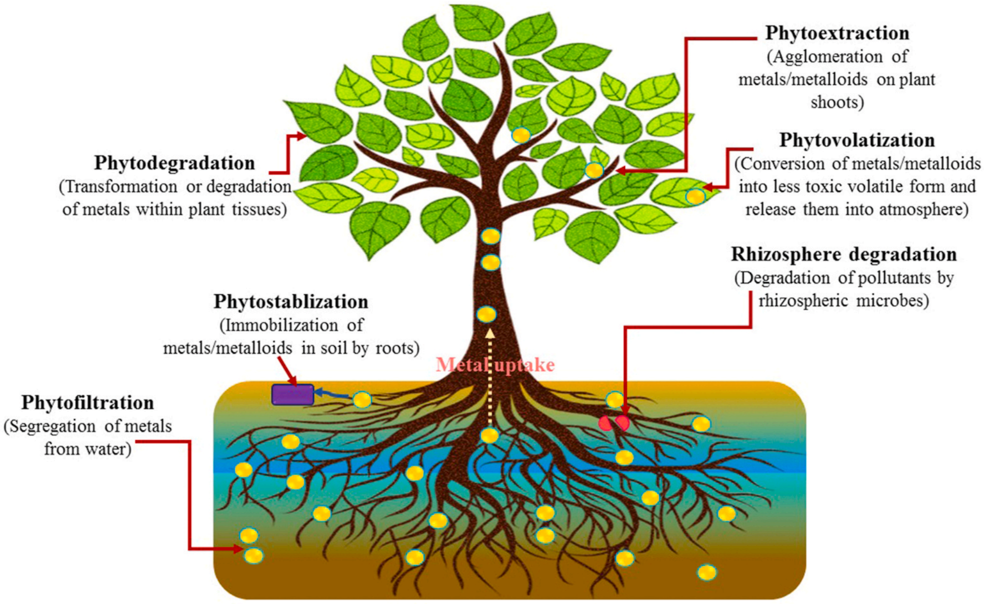

Fig. 6. Schematic representation of mechanisms operating during phytoremediation of heavy metals in the plant-soil interface.

reactions such as redox reaction, carrier uptake, precipitation of insoluble metals, involvement of microbes, etc. played a major role in HMs uptake (Clemente et al., 2005; Ahemad, 2014). Therefore, microbial mining is highly popular among researchers for the extraction of HMs from contaminated sediment.

Microorganisms are omnipresent and can survive in extreme conditions (Fls et al., 2017). Microbes have developed a potential to evade the HMs toxicity present in various environmental conditions (Ahemad, 2014). Microbes used to follow vivid mechanisms to tolerate HM toxicity in their cells, among them enzymatic purification, reduce cellular responsiveness for HM ions, cellular penetrability barriers, and active transport efflux channels are the most notable ones (Bruins et al., 2000; Wei et al., 2021) (Fig. 4). Organic contaminants are either responsible for the generation of CO_2 or H_2O or produce metabolic reaction intermediates essential for cellular growth (Peng et al., 2018).

While, in case of inorganic pollutants, microbes altered their chemical configuration, which leads to suppresses their mobility, toxicity, and bioaccessibility. The immobilization of HMs on microbial cells includes biosorption (a passive interaction between cellular membrane and HMs), bioaccumulation (accumulation of substances within an organism), bioprecipitation (conversion of free metals ions into bonded forms, e.g. hydroxide, sulphides, etc.), bioassimilation (involvement of siderophores of microbial cell for active transport), biodegradation (oxidation of organic pollutants), bioleaching (breakdown of metallic minerals and leaching of linked HMs through microbial action), and biotransformation (modifications in HMs chemical structure) (Fig. 5). Among all the interaction mechanisms biosorption, bioaccumulation and biotrasformation are the major microbial processes that affect the HMs toxicity and mobility in the system (Tabak et al., 2005). The involvement of microorganisms for the fixation of HMs contamination in sediment is very cost effective, noninvasive, and can be applied on-site using basic physical or chemical modifications (Mani and Kumar, 2014) (see Fig. 7) (see Fig. 6).

But, each coin has two sides, though microbial extraction has also some drawbacks, for instance, the technique is very time consuming; biological mechanisms are very complex, even not able to understand; can be tough to forecast the consequence of bioremediation (Tsezos, 2009; Akcil et al., 2015a, b). Yet, biological extraction technique has

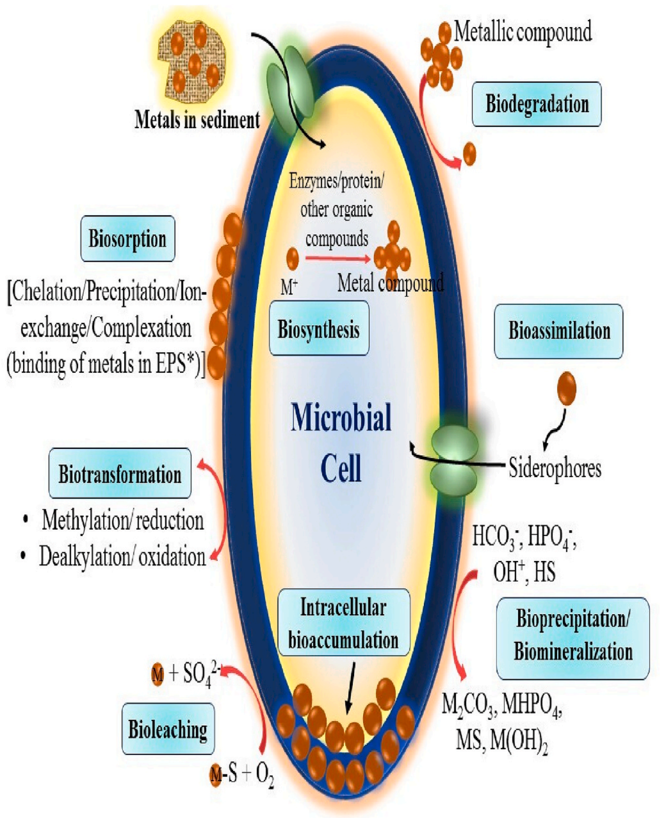

Fig. 7. Different biological processes occurred on microbial cell under heavy metal stress condition.

been extensively used by researchers, worldwide. Application of *Thiobacillus* spc. bacteria for bioleaching purposes, under aerobic and low pH conditions (pH $<$ 4) can absorb 70–80% HMs from the contaminated sediment (Mulligan te al., 2001; Gan et al., 2016). The efficiency of metal extraction is highly dependent on microbial strain and sediment characteristics. The advantages and disadvantages of each extraction method are provided in Table 2.

Table 2
Advantages and disadvantages of resources extraction methods from dredged sediments.

S. No.	Methods	Details	Advantages	Disadvantages
1.	Isolated and confined disposal and geocontainers	Storage of sediment in a confined area	Huge amount of sediment can be applied for pretreatment	Persistence of contaminants in local environment and can pollute our resources in a long term
2.	Immobilization	Stabilization of contaminants	Application of only stabilizing agents	Dewatering of sediment (moisture content <50%) required, interference of organic contaminants, and continuous monitoring is required
3.	Physical treatment	Contribution of techniques like gravity separation, screening, forth flotation, etc.	Useful for sediment with high metal load	Not suitable for contaminants linked with high fractions
4.	Washing	Involvement of washing agents to solubilize contaminants	Suitable for treatment of large fraction sized (sand and gravels) sediment	Only able to extract weakly bounded metals
5.	Electro-chemical	Usage of low-intensity current for contaminants extraction	Low volatility metals and higher extraction ability	Very costly, required high water and organic contents removal
6.	Thermal	Application of high temperature for heavy metal removal	Highly recommended for volatile metal removal	Presence of high water content increase the costs
7.	Biological extraction	Use of microbes or plants for the extraction of heavy metals	Suggested for sediments with low metal level and high gravel percentage	Time consuming and not yet examined for pilot scale application

7. Conclusions

The present work comprehends not only the problems of breach wrack and dredged sediment but also entails its management approaches practices across the globe. The removal and management of these wastes especially the beach wrack has several palpable significances in terms of recreational commitments and touristic value. The beach wrack and dredged sediments find their ultimate destination in landfills. However, these wastes have enough potential to be used as natural precursors for energy and various end-use products. The beach wracks species like *P. oceanica, Z. marina*, and *E. acorodies* can be very beneficial species in terms of economic growth. The removal of sea grasses can help in the restoration process by taking the nutrients from marine ecosystem. The species *P. oceanica* has a good amount of essential nutrients such as N, P, K, Ca, and Mg and can be applied as compost in agricultural land. However, its separation from sand mixture is essentially required. Similarly, usage of beach wrack waste in cosmetic and pharmaceutical industries can be a good substitution for chemical based products. Brown algae have shown the least potential for methane yield. In paper and textile industries involvement of beach wrack waste can be a novel idea toward sustainable practice. The biodegradable thermoplastics polymer is the demand of current world and wrack of *Z. marina* beach wrack species can be a good raw material for its production. Produced biochar and activated carbon from waste beach wracks can be a sustainable solution for soil improvement and crop yield. Indeed, biomass of species like *E. acorodies* and *P. oceanica* can be used for the generation of green electricity, at a low cost. Hence, numerous options are available for beach wrack residues management and demand further deep studies towards circular economy.

The dredged sediment can no longer be used, although various techniques have come to light for the recovery of resources from dredged sediment at pilot scale. A technique like physical treatment allows the separation of highly contaminated fine fractions of sediment from the rest of the sediments, which ultimately reduces the mass of sediment, but the problem linked with its disposal has remained the same. The usage of geo-containers like geo-textile is majorly used for dewatering dredged sediment, but insufficient information is available about the release of contaminants from it. Major techniques highlighted for the extraction of HMs include immobilization and washing techniques. The immobilization techniques are effective but continuous monitoring is required because organic debris can reduce the treatment efficacy. Vitrification process is highly suitable for contaminated sediment amendment but it is very costly. Similarly, thermal treatment is highly recommended for the extraction of volatile metals like Hg, Cd, and As but is expensive for pilot scale application. Although, with the thermal extraction process, high-grade Hg can be obtained, which could compensate for the treatment expenditure. On the other hand, biological extraction is very cost-effective and sustainable, but it is time-consuming. Overall, very few cost-effective extraction techniques are available for dredged sediment management and significantly required further advancement. It is very difficult to promote any extraction method for dredged sediment management because type, texture, and sediment conditions varied from one location to another. Although the present recovery and reuse practices for beach wrack and dredged sediment have enough potential. However, more cost-effective options considering the resource availability of the region should be tested and explored.

Credit author statement

Divya Pal: Visualization, Collection of literatures, and Writing - original draft, figures and tables preparation. William Hogland: Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113971.

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