The potential of microphytobenthos in sediment biostabilisation of aquatic ecosystems: an overview

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Abstract. Microphytobenthos represents microscopic primary producers, primarily diatoms that often form heterogeneous biofilms on sediment surface. Microphytobenthos assemblages have been documented and reported to be closely linked with the biostabilisation of the sediment surface in the intertidal flat of Europe. Flood and ebb tides cause vertical movement of the benthic diatoms in the surface of the top sediment, which contributes to stabilizing the sediment. Light, salinity and other environmental stressors further initiate microphytobenthos to move up and down vertically in the surface of the top sediment. Diatoms produce and secrete extracellular polymeric substances in response to their locomotion, which favorably stabilize the sediment surface during high tide immersion. Frequent storms caused by climate change have intensified the erosion problem along coastlines. Unfortunately, structures such as wave breakers and breakwaters that are built along some coastlines have proven to worsen the erosion rate. More environmental and biological-friendly solutions are needed to tackle the erosion problem worldwide. The widely distributed tidal flats and mangrove forests along the coastlines must harbor the diatom species that have biostabilisation potential. This review presents data that supports the biostabilisation of sediment by diatoms, provides information on this process and initiates more studies regarding the potential of microphytobenthos in biologically reducing sediment erosion along the coastlines, rather than structurally.
Key Words: biostabilisation, chlorophyll *a*, diatom, erosion, microphytobenthos.

Introduction. Microphytobenthos biomass (MPB) or benthic microalgae has been long known as the base of the food chain for sub-tidal and intertidal ecosystems. The MPB communities consists of the diatoms, cyanobacteria, chlorophytes and some other divisions of microscopic algae that normally inhabit the sediment. Diatoms however, are often the most common (Mann 1999). Viable MPB inhabits the top 10 cm of the sediment (Brito et al 2012), but it normally accumulates in the top 2 mm of the surficial sediment (Blanchard & Forster 2006). Nonetheless, even located and restricted in the uppermost part of sediment, MPB still has a significantly high impact on the functioning of whole intertidal flats and estuarine ecosystems (Colijn et al 1984; Aberle-Malzahn 2004; Blanchard & Forster 2006).

MPB is composed of autotrophic microorganisms and plays a vital role as a processor for atmospheric carbon dioxide as it takes up greenhouse gas to photosynthesize. Webster et al (2002) suggested that the photosynthetic activity of MPB also aids in the production of oxygen and the return of nutrients to the sediment. Both oxygen and nutrients are crucial to ensure the survival and sustainability of organisms in both intertidal and aquatic ecosystems. Other ecological functions of MPB include the ability to retain the nutrients in sediment by preventing the nutrients release into the water column (Underwood & Kromkamp 1999; Tyler et al 2003). In addition, photosynthesizing MPB also influences nitrogen turnover processes and helps in the phosphate exchanging process between water and sediment (Risgaard-Peterson 2003).

Motile or epipelic diatoms, which are the major constituents of MPB communities, are also vital as sediment stabilizers. These microalgae display vertical migratory rhythm that is often synchronized to the diurnal tidal activity. During the emersion (low tide) period, diatoms migrate vertically upwards, towards the photic zone, to photosynthesize and thereby accumulate on the sediment surface (Cartaxana et al 2016). Prior to high tide period, these unique microorganisms migrate downward into the sediment. This may be a survival mechanism to reduce the 'wash away' effect of the tidal action (Koh et al 2007). The upward and downward migrations of motile diatoms in the top 5 mm of the sediment surface are an important regime aiding the sediment biostabilisation. Movement of diatoms in sediment involves the production of extracellular polymeric substances (EPS) that act as an organic glue and stabilize the sediment (Underwood et al 1995), and potentially inhibit the resuspension or wash away of sediment by tidal currents and wave energy (Ubertini et al 2015). The formation of physical mats of diatoms and associated bacteria called 'MPB biofilms' on the sediment surface is reported to effectively retain sediment during tidal activity by preventing the sediment from being suspended and carried away during high tide period (Underwood & Paterson 1993; Ciutat et al 2007; Fang et al 2014). The functions of EPS on the intertidal flat ecosystem can be surmised by understanding its relationship with the physiology and biological processes of diatom communities and other microorganisms.

Chlorophyll *a*, a colloidal carbohydrate (CC), and EPS concentrations in the top 3 to 5 mm (Defew et al 2002; De Brouwer et al 2003) sediment surfaces are biomass proxies that can be used as indicators in studying diatoms. Although it is EPS that reportedly aids the sediment stability (Underwood et al 1995; Underwood & Paterson 2003), most researchers are still using either chlorophyll *a* and/or CC concentrations to study this subject. This is because the extraction of EPS from diatoms cell requires complex protocols that could lead to unreliable measurements. Samples storage procedure, medium of extraction, centrifugation timing and sulfuric acid addition process must be done with high precaution or else it may potentially lead to errors (Underwood et al 1995). Regardless, studies conducted by Taylor et al (2013) and Redzuan (2017) successfully found a strong correlation between chlorophyll *a* and EPS concentrations. This further supported the fact that the use of chlorophyll *a*, although not the substance that directly contributes to sediment stability, is still a useful proxy in studying biostabilisation.

Some important ecosystems, such as mangroves, tidal flats and estuaries, lie along coastlines. Therefore, loss of coastlines due to erosion can potentially cause catastrophic ecosystem instability. Sediment erosion has attracted the attention of many researchers. Studies have been done to characterize coastal erosion models (Awang et al 2014; Ariffin et al 2016) and morphology (Muslim et al 2011). This undoubtedly provides vital information on the nature of erosion along coastlines, especially in the Association of Southeast Asian Nations (ASEAN) countries. For instance, in Malaysia, construction of coastal defense structures is one of the approaches that is used to reduce the erosion effect by wave energy along its coastline. However, the structures only reduce the wave energy intensity and decrease the erosion rate at the shoreline behind it, but increase the wave energy effect and possibly erosion on other parts of the shore (Awang et al 2014).

Mangrove, intertidal flat and salt marsh restoration could be one of the natural approaches to control the loss of coastline to erosion. But a restoration program can be very costly. For instance, the cost to effectively restore a fully-functional mangrove ecosystem is reported to range from 225 to 216,000 USD per hectare (Lewis III 2001). In mangrove restoration projects, attention is often only given to planting mangrove trees and hydrology restoration, with the functional aspect of the mangroves as an ecosystem being neglected. One way to understand the mangroves as a fully functional ecosystem is to investigate the ability of MPB to naturally increase the erosion threshold of the ecosystem sediment. To out knowledge, no research has been carried out to exclusively reveal the biostabilisation effect of MPB on not only the sediment of mangrove ecosystem, but at a larger scale, perhaps along the active erosion that takes place in most of the world's coastlines. Therefore, this review aims not to discuss only the potential of MPB in sediment biostabilisation, but also to promote teamwork with various members of the scientific community to reveal other ecological aspects of the MPB potential.

MPB biomass and Sediment Stability. The presence of diatoms on the sediment surface of an intertidal flat can be directly depicted by the biomass, while chlorophyll *a* concentrations serve as a proxy. Basically, high chlorophyll *a* indicates high diatom biomass that can be responsible for the formation of sturdier physical mats, called biofilms. Studies carried out by Du et al (2010) revealed outstandingly high diatom biomass (by means of chlorophyll *a* concentration) on the sediment surface, even during tidal coverage (Table 1). These findings could be attributed to the thick diatom mats formed during the emersion period prior to incoming tides. This well-structured mats or biofilms were reported by Woelfel et al (2007) to form a mucous-like laminated layer on the sediment surface that can potentially hold sediment aggregates together during high tide periods. Findings by Weerman et al (2012) regarding the positive correlation between the MPB content on sediment surface and sediment bed level, further supported the diatom potential in stabilising the sediment. The work also reported that excessive grazing of diatoms by herbivorous grazers degraded the sediment biofilms and consequently led to a poor relationship between the MPB and sediment beds. Therefore, the removal of MPB from sediment surface may lead to sediment instability and sediment erosion.

Table 1

Qualitatitve approach in studying biostabilisation effect of diatoms in MPB biofilm

Reference	*Study site*	*Observations*	*Biomass proxy*
Weerman et al (2012)	Keppelbank, Waterschelde estuary, Netherlands	Herbivore grazers significantly degrade diatom biofilms; small biofilms patches are formed leading to bare mudflat.	Aerial photographs of MPB biofilms
Du et al (2010)	Nakdong estuary, Korea	The formation of high biomass during emersion (low tide) results in high diatom biomass even during high tide.	Chlorophyll *a* concentration in μg cm^{-3} dry sediment
Woelfel et al (2007)	Baltic Sea Wind flat, Germany	Laminated mat with mucous-like material and consisted of 90 % of diatom species potentially contributed to sediment stabilization.	Species composition and diatom frustule numbers

Diatom potential in biostabilising sediments attracts not only diatomists and phycologists, but also microbial ecologists (Bohórquez et al 2017), geologists and environmentalists. Collaborations between experts in various fields have made studies on this subject more interesting and informative. Comprehensive studies on the relationship between the ecology, physiology and biology of diatoms on the sediment surface and sediment particles, sediment size and sediment types provide more information about the biostabilisation properties of diatom.

Table 2 presents some of the few studies investigating the correlation between diatom biomass with sediment proxies and incorporation of sediment stability measurements, in terms of erosion thresholds. Defew et al (2002) and Tolhurst et al (2003) reported the positive effect of the vertical migration of diatoms on sediment stability. Both works measure the sudden increase in the erosion threshold due to the accumulation of diatom cells (based on chlorophyll *a* concentration) in the top 2 mm sediment surface at the beginning of low tide. Diatom biomass does not activate only in fine sediment, such as mud and clay; it also showed to increase mud and sand stability, by having the ability to stick and bind the particles even when they are suspended in the water column during high tide (Orvain et al 2012). EPS that is produced by diatoms even when suspended in water column proved to have the ability stick sediment particles, aggregating the particles (Sutherland et al 1998; Fang et al 2014). Consequently, larger sediment particles will be returned and deposited onto sediment surface by means of gravity (Fang et al 2014).

Van De Lageweg et al (2017) reported that natural MPB biofilms (extracted EPS) in sandy sediment improve the biostabilisation index of the sediment up to 21 points. In the study, the biostabilisation index was the mean value of the ratio of the erosion steer stress of MPB biofilms originated from extracted EPS and the un-colonized sandy sediment. The potential of diatoms in biostabilising sediments is proved by higher erosion threshold recorded at areas colonized with diatoms when compared to erosion thresholds from un-colonized areas. The 21 biostabilisation index score is higher than the biostabilisation index displayed by artificial industrial polysaccharides such as the xanthan gum and carrageenan (Van De Lageweg et al 2017). The sediment biostabilisation by diatoms proved to be efficient in the previously mentioned study; however, some disturbances that usually occur naturally were absent, like grazer feeders, since it was an experimental (ex-situ) output that was carried out in the laboratory.

Diatom biomass on sediment surface thickens MPB biofilms and strongly affects the incipient motion of the sediment (Fang et al 2014). Fang et al (2014) successfully modeled and theorized that diatom biofilms affect the cohesion and adhesion of sediment particles, which influence the sediment erosion threshold. The biofilms comprised of benthic pennate *Nitzschia* sp. have higher adhesion properties than cyanobacteria biofilms (Larson et al 2009). Differences in the adhesion properties between these two microalgae groups are possibly attributed to the fact that diatoms produce EPS with stickier properties than cyanobacteria. This can be confirmed by the fact that each microalgae group, species and even cell, produce different types of carbohydrates and EPS (Aslam et al 2012).

Dupuy et al (2014) carried out sequential erosion experiments of sediment biofilms including viruses, prokaryotes, nanoflagellates and diatoms using sediment samples obtained from the Marennes-Oleron Bay. They found viruses, bacteria and nanoflagellates suspended in the water column even at low friction velocities (<2 cm s^{-1}). Only diatoms remained unsuspended in the biofilms. The diatoms were found to associate with sediment and bacteria. Biofilms with diatoms and bacteria were suspended only after being exposed to high friction velocities (> 2 cm s^{-1}), which eventually disrupted the sediment bed. Friction velocities higher than 5 cm s^{-1} were required to suspend diatoms in lower sediment biofilms (> 2 mm in the top sediment). The findings may be related to the downward migration of diatoms in the sediment biofilms, which were reported to significantly produce large amounts of EPS (Smith & Underwood 1998; Consalvey et al 2004).

Another study carried out by Austen et al (1999) investigates the relationships among MPB biomass (diatoms), grazers, sediment erosion thresholds and suspended sediments. The study reported the following: the significant positive correlation between chlorophyll *a* (biomass proxy) and erosion threshold; the significant negative correlation between chlorophyll *a* and *Hydrobia ulvae* (grazers); the significant negative correlation between *H. ulvae* and erosion threshold; the significant positive correlation between *H. ulvae* density and the concentration of suspended sediments.

For an effective biostabilisation, a biofilm needs to be associated with diatom assemblages that consists of more than 50 percent living epipelic diatoms (Underwood et al 1995; Underwood & Paterson 2003; Woelfel et al 2007). Only then, the biofilms will have sufficient EPS produced by the movement of the epipelic species. This type of MPB biofilms was also reported by Underwood (1997) to successfully trap newly-deposited sediment of newly restored salt marsh in Blackwater, Essex, UK. It is reported that the biofilms stick to sediment particles and prevent them from being washed away during incoming tide (ebb tide) and high tide periods.

Table 2

Studies done to investigate the relationship between diatoms biomass and sediment erosion threshold

Reference	*Study site*	*Findings*	*Biomass proxy*	*Sediment proxy*
Defew et al (2002)	Eden estuary, Scotland and Molenplaat mudflats, The Netherlands	Diatom biomass significantly positively correlates with erosion thresholds	Minimum fluorescence	Erosion threshold (Nm^{-2})
Tolhurst et al (2003)	Tagus estuary, Portugal	Significantly positive correlation between Chlorophyll *a* concentrations of diatom biofilms and erosion thresholds	Chlorophyll *a* concentration in mg m^{-3} and LTSEM images	Erosion threshold (Nm^{-2})
Larson et al (2009)	Ex-situ and experimental	Biofilms associated with benthic *Nitzschia* sp. are more resistant to erosion due to high adhesion/cohesion compared to Cyanobacteria biofilms	MPB biofilm thickness over time	Magnetic flux density (unit: mTesla) that measured adhesion property
Orvain et al (2012)	Baie des Veys, France	Positive correlation between silt accumulations (stickiness) and diatom biofilm development	Chlorophyll *a* concentrations in μg g^{-1} dry sediment	Sediment categories (clay, silt, sand), diameter (μm) and fraction (%)
Van De Lageweg et al (2017)	Total environment simulator flume (Ex-situ)	Sandy sediments colonized with diatoms biofilms present higher erosion thresholds (up to 3.5 Nm^{-2}) compared with those of uncolonized sediments (0.18 Nm^{-2})	EPS	Erosion threshold (Nm^{-2}) and biostabilization index

EPS - extracellular polymeric substance; MPB – microphytobenthos.

Sediment biostabilization by MPB in different types of sediment. Ubertini et al (2015) present one of the few works that measures EPS as a biomass proxy when studying the relationship between diatoms and sediment erosion thresholds on an intertidal flat. The study carried out using different sediment types (pure mud and mixture of mud and sand) highlights that diatom biofilms in pure mud are more unstable than in the mixed sediment types. Sand enrichment in pure mud probably provides less favorable conditions (stress) for diatoms. The different conditions are due to different sediment sizes, aggregates and permeability. This creates stress that potentially stimulates the diatoms to secrete more EPS (Taylor et al 2013). Therefore, the mix of mud and sand has higher EPS concentrations than pure mud, and also higher erosion thresholds.

Other than particle size, another factor that affects the ability of MPB for biostabilisation is the ecosystem in which it is produced. Spears et al (2008) demonstrate that even in higher MPB biomass and higher EPS concentrations, MPB biofilms in freshwater ecosystems still display lower sediment stability than MPB biofilms of estuarine ecosystems. The high ionic concentration due to sodium and chloride ions of estuarine water enhances EPS function in sediment cohesion (Spears et al 2008; Fang et al 2014). The lower sediment cohesion ability by EPS produced in freshwater is also detailed and discussed by Larson et al (2009). The ionic nature of the seawater creates physicochemical attractions between sediment particles and causes sediment aggregation (Larson et al 2009). The force of gravity ensures that the aggregated sediment particles remain on the sediment surface (Fang et al 2014). This consequently increases the sediment erosion threshold. Although diatom-produced EPS in freshwater is not as efficient as the one from estuaries in biostabilising sediments, the substance still plays a significant role in carrying out other ecosystem functions (Gerbersdorf et al 2009).

Conclusion. MPB sediment biostabilisation has been reported in many studies, but still at an initial stage, especially in ASEAN countries. More studies on the ecology of the MPB are needed to fully understand the role as a functional sediment biostabilisation agent. This short review hopefully will inform researchers to appreciate these microorganisms that, although microscopic, have valuable potential to replace the engineered structures in reducing the shoreline erosion issue. It is strongly believed that a sustainable plan for shoreline or coastline stabilization must also include the role of MPB. Initially, it is crucial to ensure the sustainability of MPB by carrying out inter-annual monitoring and by unveiling its ecological importance.

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