Characteristics of Suspended Particulate Matter, Benthic Environmental Factors, and Their Relationship to Bivalves

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Characteristics of suspended particulate matter, benthic environmental factors, and their relationship with bivalves

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Abstract

Bivalves are of great ecological and economical importance across coastal zones around the globe. Their distribution and abundance are mainly affected by various benthic environmental factors, which includes suspended particulate matter (SPM). The relationship between bivalves and SPM have been studied in various contexts over the past decades, however, such studies have not been reviewed in recent years. Therefore, a literature review of SPM found in the marine environment, its characteristics (particle size, particle density, etc.), and how the surrounding benthic environmental factors (salinity, light availability, current velocity) influence its characteristics was carried out. It was found out that there were some specific areas that lacked or required further research e.g., microplastics characteristics, mechanism behind the positive influence of PIM in bivalve diet components that is yet to be discovered, etc. Furthermore, coastal environments have experienced huge developments and changes over the past decades and these changes would have for sure affected the SPM components and environmental conditions in coastal marine environments require updated research. The above and other gaps in knowledge for future research opportunities are mentioned at the end of the article.

Discipline: Fisheries

Additional key words: inorganic matter, microplastics, organic matter, suspension feeders, turbidity

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Introduction

Coastal zones around the globe play huge roles in the livelihood of organisms and humans living near these areas. Coastal areas provide various ecosystem services including fisheries, tourism, carbon sink, nutrient recycling, and moderation of extreme natural events (Begon & Townsend 2021). Within these services, coastal fisheries production is a vital contributor to a nation's economy and is a highly valued part of many coastal communities. For example, in Japan, coastal fisheries production constitutes about 45% of the total fishery production and it constitutes about 60% in terms of value of the total fisheries production sales because of the large number of high value species that inhabit these coastal zones (Matiya et al. 2006).

One of the highly targeted, high valued species in coastal areas are marine bivalves. Marine bivalves accounted for about 14% of the global marine production during the period 2009-2014 and from this, 89% was from aquaculture and 11% from wild fishery (Wijsman et al. 2019). Wijsman et al. (2019) further reported that marine bivalves are appreciated by consumers because of their nutritional benefits as well as their taste.

Although bivalve resources are much demanded due to its high economical value, bivalve wild populations around the globe have been declining over the past few decades. One of the many causes of this decline is the deterioration in environmental conditions of bivalve habitats worldwide, where according to Beck et al. (2011), there has been a drastic 85% decline in bivalve marine habitats globally. Ongoing research on finding out the causes of decline in wild population and strategies for recovery have been areas of interest for research over the past decades.

Suspended particulate matter (SPM) is one of the key factors that has a great influence on the behavior, ecology, and physiology of bivalves (Ward & Shumway 2004). This is due to the fact that bivalves filter seawater to obtain food and oxygen in the water column and are exposed to a wide range of living and non-living suspended materials on a daily basis. Figure 1 portrays a typical benthic environment with some of the influential environmental factors that bivalves are exposed to. As stated by Gosling (2003), in the wild, bivalves feed on a variety of SPM such as bacteria, phytoplankton, micro-zooplankton, detritus, dissolved organic matter such as amino acids and sugars. In the process of filtering seawater, bivalves also modify the coupling between seafloor and water column activities, influencing phytoplankton population dynamics and nutrient cycling (Dame 1993). Bivalves highly depend on SPM for growth and survival, and this has developed a very complex relationship. After mixing and resettling occurs in the water column due to tidal changes and wave actions, the layer right above the seabed as shown in Figure 1 forms a thin bottom layer which could be influential to bivalves. This thin bottom layer has a higher concentration of SPM for a certain period before full settlement of SPM occurs.

SPM has diverse characteristics e.g., origin, size, density, chemical component, etc., and this diversity greatly affects bivalves in many ways. Due to the complex relationship between bivalves and SPM in the natural environment, a lot of studies have been carried out in this field to create better understandings. Studies by (Fox et al. 1937, Korringa 1952, Møhlenberg & Riisgård 1978, Fegley et al. 1992, Bayne et al. 1993, Ellis et al. 2002, Newell et al. 2002) are some of the many that have focused on this relationship between bivalves and SPM.

Furthermore, various characteristics of SPM could be altered by surrounding environmental factors and therefore affecting bivalves. With the on-going changes in environmental conditions due to climate change, global warming, infrastructure development, environmental conditions and SPM characteristics change. Hence, recent updated information is needed on the current status on how present environmental factors alter SPM and finally, the effect it has on bivalves. This updated information is not available in previous reviews published more than 20 years ago; therefore, this review hopes to focus its discussion on the need for research areas that need updating due to the changes that have happened in the surrounding coastal environments over the past years. This review will focus on the discussion of (1) characteristics of SPM and their effects on bivalves, (2) benthic environmental factors and its influence on SPM, and (3) future research.

1.0 Characteristics of Suspended Particulate Matter

Various characteristics of SPM affect the physiology, behavior, and ecology of bivalves. Of these characteristics, organic and inorganic particulate matter, particle size, and particle density were considered to have the greatest effect on bivalves and therefore will be discussed in this section.

1.1 Particulate Organic Matter

Particulate organic matter (POM) is a vital component of coastal marine ecosystems, especially for marine filter feeders that depend on POM for growth and survival. In simple terms, POM in seawater originates from various species of marine plants, river run-offs, sediment disturbance and airborne materials of terrestrial origin. The source and sink of POM could be estimated using stable isotopic compositions ($\delta^{13}C$ and $\delta^{15}N$) and geochemical indicators (i.e., C/N ratio of POM) in marine environments (Chen et al. 2021, Dan et al. 2022, Xia et al. 2022). POM also includes discrete biogenic entities formed *in situ*, including plankton of wide range of sizes and palatability, bacteria, invertebrate larvae and eggs, fecal pellets, etc. POM abundance in the marine environment varies from location to location e.g., POM concentrations near a river mouth would be higher considered the terrestrial run-off and input compared to a location that has no rivers or development close by. Armstrong & Atkins (1950) reported POM concentrations of 1.6-1.8 mg L^{-1} in the English Channel, Widdows et al. (1979) 1.5-1.9 mg L^{-1} in the Lynher Estuary and Griffiths (1980) 2-5 mg L^{-1} in False Bay, South Africa. There are several ways of estimating POM content in the ocean e.g., satellite remote sensing, estimating the chlorophyll (living phytoplankton biomass) and particulate organic carbon content (Legendre 1999, Franz et al. 2015). Chlorophyll and particulate organic carbon content of POM have significant impacts on the nutritional value for bivalves (Ball et al. 1997, Legendre 1999, Franz et al. 2015, O'Connell-Milne et al. 2020, Newell et al. 2021).

For bivalves, POM is the main source of nutrition for survival and at the same time these bivalves help contribute to the carbon cycle by transporting carbon to the seafloor (Middelburg 2019). The greatest positive benefit of POM is its nutritional value and therefore has been used to some degree during the rearing period for almost all previous rearing experiments involving bivalves (Widdows et al. 1979, Bricelj & Malouf 1984, Bayne et al. 1989, Bayne et al. 1993, Hawkins et al. 1996).

However, there are also negative impacts of POM in the natural environment. Fast-growing aquaculture activities in coastal areas are increasingly affecting the source, chemical composition, and fate of POM and vice versa (Sarà et al. 2004, Jean-Marc et al. 2018). Increasing land-based, coastal development and agriculture activities have also altered the characteristics, composition and amount of POM that is released into coastal waters around the globe (Sahavacharin et al. 2022). Recently, around the globe, harmful algal blooms (HABs) causing huge increases in POM have resulted in mass mortality of many coastal species and have cost millions of dollars in loss for the aquaculture and fisheries sector (Hallegraeff et al. 2021).

Another negative impact of high abundance of POM in the coastal regions is the occurrence of hypoxia, where dissolved oxygen concentrations drop to less than 2 mg L^{-1} (Zhang et al. 2018). Bivalves in coastal areas are frequently subjected to hypoxia, especially during the summer season, and tolerance is highly species specific (Diaz & Rosenberg 1995). Wu (2002) states three ways aquatic organisms respond to hypoxic conditions, (1) attempting to maintain oxygen delivery, (2) conserving energy, and (3) enhancing energetic efficiency and deriving energy from anaerobic sources. An infaunal bivalve found in New Zealand, *Paphies australis* has evolved efficient strategies for anaerobic energy production (Carroll & Wells 1995). However, there are many species that cannot adapt to the warming and hypoxic conditions, for example, recently a study by Tomasetti et al. (2023), showed a reduced performance and survival of *Argopecten irradians irradians* when an 8-day estuarine heatwave coincided with hypoxic conditions. There are very good reasons to believe that the occurrence of hypoxia will only increase and intensify over the years, due to increase in human populations, sewage treatment plants inability to keep up with growing coastal populations, global warming, agriculture, deforestation, etc.

Furthermore, microplastics, a much more recent addition to the POM family has greatly captured the interests of researchers due to its vast usage and great negative impact on marine ecosystems, and therefore will be discussed in this review. Thompson (2015) defined microplastics as a collective term that describes a truly heterogeneous mixture of particles ranging in size, from a few micrometers to several millimeters in diameter; including particles of several shapes from completely spherical to elongated fibers. In 2010, a total of 4.8 – 12.7 million metric tonnes of plastics entered the oceans worldwide and the yearly input is predicted to increase by an order of magnitude until 2025 (Jambeck et al. 2015). Plastics are accumulating in all parts of the oceans: at the surface, in the water column and in the sediments (Moore et al. 2002, Thompson et al. 2004, Barnes 2005). Plastics breaking down into micro particles are becoming part of SPM in the natural environment. Due to most plastic particles being <5 μm in size (Thompson et al. 2004, Claessens et al. 2011), it can be taken up by a wide range of marine organisms, however, since majority of all plastics are fragments, they will finally sink to the bottom and benthic invertebrates (e.g., bivalves) are the ones most vulnerable to this form of pollution. Since microplastic pollution has been an on-growing global issue, there have been many interests into the negative effects these plastics might have on our marine ecosystem. The ingestion of polystyrene microplastics by Pacific Oyster *Crassostrea gigas* affected the larval development of offspring, endocrine disruptions and energy usage and storage (Sussarellu et al. 2016). Prolonged exposure time to microplastics in *M. edulis* showed notable histological changes and strong inflammatory responses (von Moos et al. 2012).

Nonetheless, microplastics do not only directly affect the physiology of bivalves but also indirectly affect them by changing the structure of their sedimentary habitats and delivering persistent organic pollutants (Zhang et al. 2020). Seeley et al. (2020) stated that the presence of microplastics altered sediment microbial community composition and nitrogen cycle in salt marshes. Furthermore, not until recently, researchers have highlighted the possibility of marine microplastics being a potential plastic debris that acts as a novel substrate for pathogens, in particular marine bacteria such as vibrios, and as carriers of antimicrobial-resistant bacteria. (Zettler et al. 2013, Amaral-Zettler et al. 2020, Bowley et al. 2021). Masó et al. (2003) confirmed that drifting plastic debris has been identified as a potential vector for dispersing harmful algal bloom (HAB) species. Detailed microscopic examination of plastic debris collected at several places in Costa Brava showed that patches identified benthic diatoms and small flagellates (<20 µm) e.g., resting cysts of *Ostreopsis* sp. And *Coolia* sp. (Masó et al. 2003).

Baroja et al. (2021) in a review article stated that majority of the evidence of the impacts of microplastics on marine organisms came from experimental studies under controlled laboratory conditions and to assess the impact of marine plastic pollution on coastal marine bivalves, it is important to understand how relevant the conditions used in the laboratory exposure studies are to the conditions observed in natural marine systems. The review article performed a systematic review of the experimental studies assessing the impact of microplastics on bivalves and extracted data on the species of bivalves used, the characteristics of microplastics tested, and the responses monitored during exposure. Baroja et al. (2021) concluded that 23% bivalve exposure studies did not report critical information on the microplastic characteristics like shape and type and to allow replicability of experimental procedures, it would be essential that future exposure studies provide details on the characteristics of microplastics.

In summary of this section, it is vital to understand the characteristics and composition of these organic particles, updated on-going changes in coastal environments, especially due to coastal developments, how these changes are affecting these organic particles and finally, how these organic particles would affect the behavior and physiology of marine bivalves.

1.2 Particulate Inorganic Matter

Particulate Inorganic Matter (PIM) is the most abundant form of SPM in marine ecosystems and therefore, the role it plays will be discussed in detail in this section. PIM are complex assemblages of mineral, biogenic and anthropogenic materials including mud, silt, sand, and colloidal aggregates. Terrestrial runoffs during a heavy rain or storm are the main contributors to PIM because the runoffs mainly include silt and clays, highly charged particles which flocculate on contact with seawater. In addition to terrestrial runoffs, PIM enters the marine environment through air and dry deposition with rainfall e.g., volcanic ash and dust (Agarwal 2009). In estuaries, PIM is typically the dominant constituent and is 70-80% by mass of the SPM (Oviatt & Nixon 1975).

As mentioned earlier, the negative effects of PIM, especially on marine bivalves in accordance with previous studies will be discussed in detail. Since most marine bivalves (except for deposit feeding bivalves e.g., Tellinidae) depend on SPM as a source of nutrition, an increase in PIM concentration in the water column reduces the amount of organic particles ingested by marine bivalves due to dilution of POM concentration and results in constrained energy gain (Widdows et al. 1979, Bricelj & Malouf 1984, Bayne et al. 1993, Hawkins et al. 1996). Suspension-feeding bivalves cope with high levels of PIM by: (i) decreasing clearance rates and (ii) selectively ingesting favorable organic food particles and rejecting PIM through psuedofeces production (Widdows et al. 1979, Griffiths 1980, Bricelj & Malouf 1984). Marine bivalves that ingest inorganic particles with increasing PIM concentrations could cause a reduction in gut residence time for food particles and result in low assimilation efficiencies (Madon et al. 1998). Thrush et al. (2004) stated that inorganic silts and clays directly affect suspension-feeding animals by clogging feeding structures (gills and labial palps), interfering with particle selection, and requiring the use of energy to clear up unwanted particles. Majority of studies have stated that PIM has negative impacts on the behavior and physiology of marine bivalves (Bricelj & Malouf 1984, Robinson et al. 1984, Stevens 1987, Iglesias et al. 1996, Navarro & Widdows 1997, Madon et al. 1998, Thrush et al. 2004).

However, there are some studies that state that with the right amount of PIM concentration mixed with POM in water column, bivalves seemed to have experienced growth through greater organic absorption due to higher clearance rates and/ or higher absorption efficiency (Winter & Langton 1976, Griffiths 1980, Kiørboe et al. 1980, 1981, Møhlenberg & Kiørboe 1981). For example, Møhlenberg & Kiørboe (1981) studied the influence of natural silt (0-20 mg L^{-1}) in addition to unicellular algae cells (0-20,000 cells mL^{-1}) on the clearance, growth, and energetics of blue mussel *Mytilus edulis* and found that an addition of 5 mg silt L^{-1} increased clearance rate from 32 to 43% compared to the clearance rate of pure algal suspension. Bayne (1998) theory on regulation of filtration and feeding in bivalves might be the possible explanation to the above results. Assuming that filtration is physiologically controlled on the nutritional needs of the bivalve and qualitative and quantitative composition of SPM, Bayne's theory states that bivalves under conditions of low food environments are able to increase absorption of ingested particles during the digestion process. This theory was proven for mussel *Mytilus edulis* and scallop *Placopecten magellanicus* where higher absorption of organic matter during periods of low food concentrations in SPM was observed (Bayne et al. 1993; Cranford & Hill 1999). On the contrary to Bayne's theory, Jørgensen's theory states that bivalve feeding processes are automated and dependent only on characteristics of certain species (Jørgensen, 1996). Clausen & Riisgård (1996) experimental results supported this theory by showing that for mussel *Mytilus edulis*, there were no physiological regulation of the filtration rate to nutritional needs, and that food uptake in nature is characterized by the full exploitation of the capacity of the bivalve filter-pump. The theory is true and more reflective of bivalves feeding behavior still remains unclear and needs to be further investigated.

1.3 Particle Size

Particle size of SPM is a very vital part of the survival of marine filter feeders as these organisms depend and actively select particles on their sizes when filter feeding. As emphasized by Balasubramanian et al. (2020), particle size of SPM is an important characteristic and plays an important role in the biogeochemical and ecological processes of complex coastal environments. Several studies have shown that particle size distribution have important impacts on ocean processes, such as settling velocity of particles, carbon fixation, and light availability in the water column (Xi et al. 2014, Qiu et al. 2016, Nasiha et al. 2019). Table 1 summarizes a list of previous studies on the influence of particle size on various bivalve species.

Early studies suggested that bivalves could successfully capture particles in the sub-micron range, however, later studies in the mid 1950s using *Mytilus edulis* demonstrated that capture efficiency for particles <2.5 μm in diameter was considerably low (Fox et al. 1937, Fox & Coe 1943, Korringa 1952, Tammes & Dral 1955). Tammes & Dral (1955) showed that particle capture was dependent on the diameter of particles, and that in mixed suspensions of particles of different sizes, each component is removed as it were separate using a sieving mechanism in the laterofrontal cirri. Later, as shown in Table 1, Møhlenberg & Riisgård (1978) studied the retention efficiency of 13 bivalve species and found out that retention efficiency decreased with particle size, and the particle diameter at which inefficient retention began were species specific. All bivalves studied could capture particles >6 µm in diameter at near 100% efficiency, however, some species like the ocean quahog *Artica islandica*, as shown in table 1 could retain 1 µm particles with an efficiency of about 60-70%. Generally, capture efficiency of particles increases non-linearly with increasing particle size to a maximum (Ward & Shumway 2004).

Moreover, *M. edulis* can feed on particles ranging in sizes from 3 to 110 µm (Newell et al. 1998), although the species has also been recorded to consume zooplankton up to several hundred microns (Davenport et al. 2000, Lehane & Davenport 2002, 2004) and has 100% retention efficiency when feeding on particles of >6 µm (Møhlenberg & Riisgård 1978) and 50% retention efficiency when feeding on particles of 2 µm (Newell & Shumway, 1993). In addition, a more recent study by Suzuki et al. (2022) reported dead but incompletely digested zooplankton bladder moon snail *Glossaulax didyma* larvae shells were found in the feces of pen shell *Atrina lischkeana* collected off the shores of Isahaya Bay, Japan.

Retention on bivalve gills is at least partially dependent on particle size since the ctenidium does not retain the smallest particles with 100% efficiency (Riisgård 1988, Barillé et al. 1993, MacDonald & Ward 1994). Several researchers have made observations on dissected bivalves, which indicated a rotation of style and beating of ciliated tracts creating a circulation of fluids within the stomach (Reid 1965, Purchon 1987). Crystalline styles are transparent rods found in the digestive system of all bivalves except protobranchs that plays an important role in sorting of food particles (Kristensen 1972). For example, in oyster *Crassostrea gigas*, the crystalline style functions by mechanically pressing nutritious particles against the absorptive epithelium of the style pouch and observations showed that when the specimen was held out of water, the crystalline style disappeared and reformed after being submerged an hour later (Bernard 1973). To make things more complicated, there are studies that reported lower capture efficiency of larger particles compared to small particles (Lesser et al. 1991, Bougrier et al. 1997, Pile & Young 1999) and these is difficult to explain. A review article by Ward & Shumway (2004) states that differences in cell shape or flexibility significantly influences particle capture. Bayne et al. (1977) reported that elongated or tri-radiated cells maybe more efficiently retained than spherical particles of the same volume. Another possibility is that swimming cells interact with ctenidium of some bivalve species in different ways e.g., Bricelj et al. (1998) reported that diatom of size 11 µm, *Thalassiosira weissflogii* were entrained in the anteriorly directed slurry in the dorsal ciliated tract, but toxic and non-toxic strains of dinoflagellate (Alexandrium spp.; 35 µm length) were not retained on the frontal surface of the ctenidium. Particle size selectivity is different from species to species; therefore, further studies are required for individual particle size selectivity preferences.

1.4 Particle Density

Particle density which refers to the amount (weight) of suspended particles in a volume of water is an important characteristic of SPM that needs to be studied and as it has several impacts on the ecology of the marine environment. Increase in SPM density in estuaries or bays are mainly caused water discharged by rivers and by the resuspension of fine sediments during periods of high current velocity on flood and ebb tides, and wind-wave activity (Navarro & Widdows 1997). Navarro & Widdows (1997) further explains that while the above processes results in an increase in total POM, the relative content of POM can be reduced because of the higher abundance of PIM in the resuspended sediments.

SPM concentrations in coastal waters typically range from a few mg L^{-1} to several tens of mg L^{-1} (Oviatt & Nixon 1975). However, there are some places, for example, an estuary in New Zealand experiences rise in suspended sediment concentrations from 10-20 to 1000 mg L^{-1} during a storm (Fahey & Coker 1992). In countries like Japan, river outflows are controlled, and this type of outflow controls influences particle density of SPM (especially POM density) in nearby areas (personal communication). Depending on the tidal conditions at the time of input, sediments will either be transported out of the estuary or be deposited. If deposited and available for resuspension, the bottom waters (as shown in Figure 1 thin bottom layer) will experience high levels of particle density and therefore impact benthic communities, especially, benthic filter feeders like bivalves.

Table 2 summarizes previous findings on the effect of particle density on various bivalve species. Increased concentrations of PIM (e.g., clay and silt) in suspension may increase psuedofeces production, which would decrease the amount of organic food ingested and could damage the gills of filter feeders and limit bivalve growth (Bricelj & Malouf 1984, Robinson et al. 1984, Stevens 1987, Iglesias et al. 1996, Navarro & Widdows 1997, Snyder et al. 2017, Palmer et al. 2020). Furthermore, Robinson et al. (1984) previously showed that suspended sediment concentrations as low as 100 mg L^{-1} had negative effects on bivalve energetics. Bricelj & Malouf (1984) also showed evidence that fine grained sediment concentrations as low as 40 mg L^{-1} reduced clearance rate by 52% relative to the control and inhibited growth of hard clams *Mercenaria mercenaria* (Table 2). Ellis et al. (2002) laboratory experiment results showed that sediment concentrations as low as 80 mg L^{-1} had adverse effects on horse mussel *Atrina zelandica.*

Decrease in filtration rates is one of the main reasons why particulates of high density have adverse effects on bivalves but has yet to be clearly understood. Observations on dissected bivalves indicate particle density may be a factor in sorting in the bivalve stomach (Reid, 1965) but have yet to be studied in intact bivalves. Jørgensen (1996) reported that increased particle density can also have a negative effect on the feeding behavior of suspension feeding bivalves. To help address this gap in research, Brillant & MacDonald (2000) conducted an experiment to determine whether sea scallop *Placopecten magellanicus*, can sort particles within the gut based on density alone and found out that lighter polystyrene beads were retained longer than the heavier glass beads.

However, the effects of particle density are strongly affected by lab-outdoor difference, acclimation of experimental animals to experimental conditions, and size distribution of particles (Fréchette & Grant 1991, Cole et al. 1992, Jørgensen 1996). Therefore, when conducting laboratory experiments, it is vital to keep in mind that the experiment validates the situation and conditions of the natural environment. Following these suggestions, several studies were carried out under field conditions to study bivalve responses to increasing concentrations of natural SPM and results suggested that continuous interrelated changes in feeding physiology can help to maintain rates of nutrient acquisition independent of short-term fluctuations in SPM composition (Hawkins et al. 1996, 1999; Urrutia et al. 1996, Ellis et al. 2002). An example that covers every aspect of the natural conditions is the study by Ellis et al. (2002), which focused on the physiological conditions of horse mussel *A. zelandica* when exposed to different suspended sediment concentrations. There were three parts to this study which included a laboratory experiment, a field survey and finally, a field experiment. Across all fields and experimental conditions, results obtained demonstrated a negative relationship between suspended sediment concentrations and the physiological conditions of *A. zelandica* (Ellis et al. 2002).

There have been many studies that have been carried out to show the relationship between SPM concentrations and the physiological effect on marine bivalves (Navarro et al. 1992, Iglesias et al. 1992, Bayne et al. 1993, Navarro & Widdows 1997). High filtration rates would be more favorable to increase energy gain during turbid conditions, because marine bivalves could process larger amounts of particulate matter. Since most of these studies were carried out in the late 1900s, it is necessary to carry out more of these similar experiments or modify them to confirm if the response of bivalves to different SPM concentrations is the same compared to the experimental conditions used decades ago. Dafforn et al. (2015) stated that over 50% of the world's coastline has been modified by hard engineering, including seawalls, groins, and breakwaters, which are constructed for land reclamation, fishery practice, coastal protection from erosion, flooding, and storm strikes. For example, a dike was built to help prevent coastal flooding in Isahaya Bay, Japan in 1997, and this resulted in 1500 ha loss of tidal flats, which not only destroyed the nursery ground for many fish and microbenthic invertebrates, but also decreased the purification ability of this ecosystem (Sasaki 2017). Sasaki (2017) further stated that before the reclamation of land, benthic species were able to function as a natural water purification system, but now, without the tidal flats, the concentrations of total nitrogen (TN), total phosphorous (TP) and chemical oxygen demand (COD) in the regulating reservoir sometimes exceed the environmental quality standard. Four months after the enclosure, Sato (2001) reported mass deaths of 73 ind. m^{-2} of the bivalve *Tegillarca granosa* (3-5 cm in shell length) that inhabited the muddy tidal flats in the inner part of the bay. Therefore, the reason for this suggestion is because coastal areas have undergone huge developments and modifications over the past decades and these changes have greatly influenced and changed the components of SPM in coastal marine environments.

2.0 Benthic Environmental Factors vs. Suspended Particulate Matter vs. Bivalves

This section will focus on an order of how several benthic environmental factors (i.e., salinity, light availability, and current velocity) influence SPM compositions and how these influences on SPM affect the behavior and physiology of bivalves (Fig. 1). These benthic environmental factors might have direct effects on bivalves, however, for this review we will be not focusing on the direct effects but focusing on the effect of these benthic environmental factors on SPM characteristics and composition. We will discuss benthic environmental factors that have great influence on SPM characteristics and composition in coastal areas.

2.1 Salinity

We will discuss the effect of salinity on SPM characteristics and finally how SPM would impact the physiology of bivalves. Coastal areas are known for their remarkable spatio-temporal fluctuation in environmental factors, one being the huge fluctuation in salinity due to river flow inputs of freshwater which decreases salinity levels and then well-mixing through various physical processes e.g., tidal changes and wave actions. Therefore, it is important to further investigate the effects of salinity on SPM characteristics within coastal zones and find out how this would later have an impact on marine bivalves.

According to previous studies, through competitive, complexing and electro strictive effects on seawater ions (Bourg 1987, Gschwend & Schwarzenbach 1992), and modification of sorptive properties of SPM by interactions between particle surface and substances dissolved in seawater (Turner & Rawling 2001), salinity affects the partitioning of trace chemical constituents. Salinity does have its influence on SPM by creating aggregation of suspended particles in the natural environment. Salinity in the environment influences flocculation/ aggregation of SPM which affects particle size and surface area and therefore affecting settling velocity: for example, the higher the salinity, the greater the flocculation of SPM and the bigger the flocs, the faster the settling velocity (Kranck 1973, 1981, Lick et al. 1992). Priya et al. 2015 stated that a particle settling in a water column is affected by the density of the water owing to salinity stratification and therefore influencing the settling velocity of the particle. This study further stated that a higher salinity gradient caused higher density at the bottom causing more viscosity forming flocs. The flocs, being lighter than the denser water at the bottom remained in suspension resulting in a decrease in settling velocity. In southern Japan, Nishimura et al. 2011 reported that 'concentration based' settling velocity of the suspended mud increased with increase in salinity at the tidal river of Chikugo River. In another study, Joen et al. 2011 studied the influence of salinity and organic matter on the distribution coefficient (K_d) of perfluorooctane sulfonic acid (PFOS)and perfluoroooctanic acid (PFOA) in a brackish water clay system. Results showed that the distribution coefficients (K_d) for PFAs onto inorganic clay surfaces increased with salinity, providing evidence for electrostatic interaction for the sorption of PFAs, whereas the relationship between K_d and organic carbon content (f_{oc}) suggested that hydrophobic interaction is the primary driving force for the sorption of PFAs onto organic matter. Enhancement of sorption of PFAs to particulate matter at high salinity values could evoke potential risks to benthic organisms in estuarine areas. From these studies, it could be seen that salinity along with other environmental factors (e.g., seawater temperature) play a huge role in the distribution of SPM, especially POMs in coastal estuarine environments.

The influence of salinity on SPM stated above would further have an effect on marine bivalve in terms of (1) changes in SPM particle size, (2) changes in SPM settling velocity and (3) changes in SPM electrical characteristics (Kranck 1973, 1981, Bourg 1987, Gschwend & Schwarzenbach 1992, Lick et al. 1992, Hernroth et al. 2000). Therefore, when considering the effects of SPM on bivalves, a more holistic approach should be taken to better understand the complex relationship between environmental factors such as salinity, its effects on the characteristics of SPM and later on how these changes to SPM would affect benthic organisms such as bivalves.

2.2 Light Availability

Light availability has profound effects on a wide variety of aquatic processes, but for this review we will be mainly focus on effects that light availability has on SPM in the marine environment. According to Wofsy (1983), light availability maybe the most important factor controlling biomass-specific productivity. The most studied area under this subtopic is the primary role of light availability as a source of energy for phytoplankton photosynthesis. Phytoplankton falls under the POM category so therefore light availability will indeed have an effect on the abundance of POM in the natural marine environment. In addition to that, in terms of effects on SPM, light availability affects water transparency (Scheffer 1998), algal competition (Huisman & Weissing 1994, Huisman et al. 1999, Reynolds 2006), phytoplankton biodiversity (Reynolds 1998, Stomp et al. 2004) and seston stoichiometry (Hessen 2006).

Distribution of water turbidity and light transmission in coastal areas are strongly influenced by sediment moving from land-based sources through rivers and estuaries (Bell et al. 2015). Knowledge of seawater properties such as turbidity and light transmission are essential to understanding the conditions of coastal environments (Azis Ismail & Prayitno 2020). The relationship between light availability and suspended POM in the water column is a mutual relationship (Azis Ismail & Prayitno 2020), however, not the same could be said for the relationship between light availability and suspended PIM. Light availability might not have much influence on PIM, but inversely, PIM does have great influence on light availability because as PIM concentrations increase after huge freshwater inputs directly and through rivers from heavy downpours or changes in tides, coastal water turbidity levels sharply increase causing lower light availability. On the other hand, light penetrating through the water column will allow primary production by phytoplankton (light dependent) which will increase POM densities in the water column and hence drive the microbial food web that takes place down to depths of the euphotic zone (Gameiro et al. 2011). Gameiro et al. (2011) reported that light availability was the main limiting factor for low primary production, despite the presence of high nutrient concentrations from high freshwater input and strong tidal currents in the Targus estuary, west coast of Europe. Maung-Saw-Htoo-Thaw et al. (2017) reported similar results where monsoon season off the coast of Myeik City, Myanmar delivered heavy precipitation bringing great amounts of terrestrial nutrients to the coast, but on the other hand, coastal waters were affected by the turbid waters which limited light penetration into the water column resulting in a decrease in primary production.

Over the recent years, harmful algal blooms (HABs) has been an area of growing interest as it has cost the fisheries and aquaculture sector millions and millions of dollars. Since HABs contribute to the overall density of POMs and light availability being one of the contributing factors, this area should be studied in more detail to help understand and control HABs around the globe.

2.3 Current Velocity

Current velocity is strongly influential on the characteristics of SPM e.g., SPM density, and therefore reviewed in this article for better understanding. As shown in table 3, there are several studies that have reported about the effects of current velocity on bivalves (e.g., filtration rates, clearance rates) (Wildish & Miyares 1990, Newell et al. 2001, Widdows et al. 2002), but the effects of current velocity focusing on SPM characteristics and composition are poorly studied.

Current velocity near the seabed is likely to affect the availability of SPM and also the feeding behavior of bivalves (e.g., high speed currents causes detachment of bivalves from their substrates, stagnant conditions causes particle settlement with high SPM densities directly above the seabed, and optimal current speeds provide the best conditions for maximum feeding). Bottom high-speed currents may result in direct physical impact on mussel performance, or the erosion/disturbance of the underlying sediment; while at reduced speeds the mussels can influence their surrounding environment by depleting food downstream (Fréchette & Bourget 1985a, Fréchette et al. 1993). At higher current velocities directly above a natural mussel bed, phytoplankton depletion was low compared to mussels elevated in the water column above the food-depleted zone which grew faster than those near the bottom (Fréchette & Bourget 1985a, b).

Moreover, currents caused by continuous tidal changes triggers resuspension of benthic sediments and result in a higher SPM density in the water column that barely causes resettlement due to the on-going tidal changes. On the other hand, currents caused by strong winds and wave actions are not continuous and happen from time to time resulting in resuspension of benthic sediments. Once the driving force of these currents weaken, sediments resettle to the bottom often accumulating on the surface of bivalves at various thicknesses disrupting their filtering activity. Yurimoto et al. (2008), in a laboratory experiment, tested the influence of resuspended sediments and their surface accumulation on pen shell *A. pectinata*. Results from this study stated that resuspended sediments is one of the efficient food sources for pen shells, but accumulation of sediments (resettlement) over 10 mm thickness increased glycogen consumption and fatality risk due to the organism trying to avoid burial. Sediment accumulation experiments that might cause suffocation and influence the physiological state of bivalves should be further investigated.

As shown in table 3, Wildish & Miyares (1990) reported that *Mytilus edulis* experienced a decrease in filtration rate with increasing current velocities from 0.06 to 0.22 m s^{-1} and flows >0.25 m s^{-1} resulted in filtration rates <10% and remained this way up to flow speeds of 0.38 m s^{-1}. Later on, Newell et al. (2001) results indicated that *M. edulis* decreases its filtration rates as current speeds increase from 0.1-0.3 m s^{-1}, probably due to unfavorable hydrodynamics (pressure differential). Current speeds ranging from 0.1-0.3 m s^{-1} had a highly significant linear decrease in exhalent siphon area but no effect on valve gaping of *M. edulis* (Newell et al. 2001). A study by Sobral & Widdows (2000), reported that an infaunal bivalve species, *Ruditapes decussatus* recorded maximum clearance rate up to a current speed of 0.08 m s^{-1} and as current speeds surpassed 0.17 m s^{-1}, clearance rate decreased with sediment erosion and movement (Table 3). Using annular flumes to determine the influence of current velocity on infaunal deposit feeding bivalve, *Macoma balthica*, Widdows et al. (1998) stated that *M. balthica* was found to increase the sediment resuspension (due to burrowing/ or feeding activity) by 4-fold, at densities similar to those recorded at the Skeffling mudflat (Humber estuary) (i.e., >1000 ind. m^{-2}). There was a significant correlation between sediment resuspension and *M. balthica* density (r=0.99; ****P*<0.001), which supported previous in-situ field observations indicating bioturbation by *M. balthica* enhanced sediment erodibility.

Movement of water and the speed of movement is very important in the transportation of nutrients and oxygen and other SPMs in the aquatic environment. Especially, for sessile organisms like bivalves that greatly depend on water currents to deliver nutrients within their reach. There are upper and lower limits of tolerance to current velocities (Widdows et al. 2002) and some of these bivalve species have been studied as shown in table 3. For each bivalve species, finding this upper and lower limit of current velocities would be an area of interest that requires further investigation.

3.0 Future Research

After carrying out a literature review on studies and research related to SPM, benthic environmental factors and bivalves, the authors point out certain ideas and specific areas for further investigation for future research.

Firstly, most of the previous studies that examined the effects of SPM on bivalves used artificial diets and it was recognized that very different responses were observed in bivalve when fed natural suspensions of lower organic content (Foster-Smith 1975, Navarro et al. 1992, Iglesias et al. 1992, Cranford & Gordon 1992, Bayne et al. 1993). Physiological responses when fed natural suspensions of lower organic content included increase in psuedofeces production (Iglesias et al. 1992), increase in filtration rate and selection efficiency with high psuedofeces production (Bayne et al. 1993). Cranford & Gordon 1992 reported sea scallops *Placopecten magellanicus* experienced a reduction in filtration rates when bentonite concentrations exceeded 6 mg.dm^{-3} and level lower than 1.0 mg.dm^{-3} enhanced filtration rates. Furthermore, Doering & Oviatt (1986) mentioned that when applying different models of feeding behavior to field populations of bivalves, data that had been collected from experiments carried out using natural suspensions of particulates agreed with observed processes. Therefore, for future research purposes, it would be best that experiments be carried out in the natural environment or else in a way that best mimics the natural environmental conditions where changes and fluctuations of environmental factors like feed concentrations and availability, salinity, sea water temperature, etc., are reflective of natural environmental conditions.

Secondly, the mechanism that is involved in the positive effects of PIM addition to bivalve diets. The main reason behind this argument is that traditionally, adding silts and other inorganics may overload the filtering mechanism and limit ‘dilution’ the amount of material ingested (Jørgensen 1966, Widdows et al. 1979). However, it has been proven that adding silt to artificial algal diets enhanced growth in suspension feeding bivalves (Winter & Langton 1976, Griffith 1980, Kiørboe et al. 1980, 1981, Møhlenberg & Kiørboe 1981). As mentioned earlier, under subheading 1.3 Particle Size, several studies have looked into crystalline styles that play an important role in particle sorting and selection (Kristensen 1972; Bernard 1973), but more investigation regarding what specific mechanism is causing this positive effect of PIM inclusion is an interesting and challenging area for future research.

Thirdly, temporal variation pattern of SPM characteristics affects the response of bivalves. Newell & Shumway (1993) and Hewitt & Norkko (2007) explained in detail about the importance to investigate the effects of variations in stress duration on bivalves. For example, after investigating the increased sediment concentration stress effects on suspension feeding bivalves (*Austrovenus stutchburyi* and *Paphies australis*) through short-term laboratory and long-term field transplant experiments, Hewitt & Norkko (2007) found that short-term (2-days) feeding responses did not reflect feeding or biomass responses, but strong biomass responses were observed after three months in the field. The effect of duration of exposure and method of exposure (gradual exposure) should be considered important for future laboratory and field experiments.

In addition, it has been noticed that experimental individuals of the same species in the same experiment show great differences in responses against the same treatment. Widdows et al. (1979) stated that high variance in clearance rate data due to individual variation made it difficult to mask the effect of particle concentration over the narrower range of concentrations studies in laboratory experiments. As examples, refer to Figure 5 of (Ellis et al. 2002) and Figure 6 of (Hawkins et al. 1999) to observe big variations in individual data. Strohmeier et al. (2009) also reported a large individual variation in clearance rates (refer to Fig. 4). Therefore, it would be best to further investigate the reason for these variations and how these variations would impact the final results or conclusions for exposure experiments.

Another area of current research interest are marine microplastics and plastic concentration in the oceans is continuously increasing around the globe and are poisoning many of our marine organisms, and there might be still many unknown effects plastics might have on the marine ecosystem (Wang et al. 2018; Alimba & Faggio 2019; Baroja et al. 2021; Wang et al. 2021). Plastic debris have entered the diverse invertebrate and vertebrate species eliciting varieties of toxicological effects (Gall & Thompson 2015), and the potential for plastic debris to transport organic and inorganic hazardous chemicals from land to marine environment, and to humans via feeding pathways have gained alarming concerns across the globe (Teuten et al. 2009; Holmes et al. 2012). With the studies carried out in the past, there is an urgent need for a better understanding of microplastic characteristics, microplastic toxicology and multiple effects of microplastics on aquatic systems, to inform adequate mitigation and prevention strategies for this global issue (von Moos et al. 2012, Baroja et al. 2021).

Lastly, it would be groundbreaking to develop a method or technology that acts as a health indicator when carrying out exposure experiments without having to kill the bivalve. A recent study by Martinović et al. (2022) evaluated the short-term hyposalinity effect on the physiological state of pen shell *Pinna nobilis* by using a non-invasive heart rate recording sensor. Another is a biosensor developed by Wu et al. (2022), that records real-time remote stress in fish and hopefully a similar design could be used for bivalves in the future. Such advancement in technology would allow researchers to carry out experiments over longer periods of time and provide more precise data without having to sacrifice the test animals.

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