Chapter 1
Introduction

1.1 Coastal region/area

Coastal regions serve as transitional areas between land and sea (Figure 1.1), as well as key centres for transporting goods and energy. They also play a vital role in integrating various geological, chemical, biological, and physical interactions (Hou *et al.*, 2022). Even though the coastal areas are transition areas, various boundaries both toward the land and the sea are established worldwide for management purposes, some being fairly specific while others are more ambiguous. This means that the boundaries of a coastal area may change over time as the relevant issues become more extensive or complicated. Additionally, the natural ecosystems have their boundaries regardless of human interests. Therefore, to clearly understand the coastal region and its ecosystems, it is important to differentiate between the terms 'coastal zone' and 'coastal area'. 'Coastal zone' refers to the geographical area as defined by the laws governing coastal management, while 'coastal area' is used more broadly to describe the natural coastal landscape (Scialabba, 1998).

Figure 1.1 Coastal area during low tide

The coastal area is rich in diverse habitats, supporting a wide range of plant and animal life. Given the contributions of agriculture, fishing, ports, tourism, and other industries to the local economy, the coast holds great ecological and socioeconomic significance (Mejjad *et al.*, 2022; Pascoe *et al.*, 2023). The coastal zone, characterized by the intersection of the atmosphere, lithosphere, and hydrosphere, represents a highly dynamic natural system. This area acts as a transitional space where freshwater and land intersect with saltwater, facilitating the exchange and alteration of effects between land and ocean. Given its role as a habitat for many endangered species, urgent measures to address climate change are needed in this region (Ayyam *et al.*, 2019).

Coastal region encompasses several crucial and distinctive ecosystems, positioned at the interface of marine and terrestrial environments with unique climatic characteristics. However, human activities have altered the functioning of several important natural ecosystems to accommodate agro-ecosystems and urban centres (Alongi, 1997). Marine, estuary, and coastal wetlands often benefit from nutrient flows from the land and ocean upwelling, resulting in unique coastal ecosystems with rich biological diversity and valuable natural resources. Examples of such habitats include estuarine areas, coral reefs, coastal mangrove forests, tidal flats, and seagrass beds, which serve as essential nursery and feeding areas for numerous aquatic species (Ramesh *et al.*, 2015).

Over the last few decades, the combined pressures of population growth and climate change have significantly accelerated the alteration and disruption of these ecosystems, adversely affecting biodiversity, habitat suitability, and ecosystem services (Virginia & Davidson, 2012). Globally, almost 50% of salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of seagrasses have been lost or degraded (Barbier, 2017). Compared to the open ocean, the coastal zone is of significant practical relevance since it has significant human activity and is rich in biological activity (Mahrt, 1999). Coastal regions are valuable resources with significant ecological roles (Angulo *et al.*, 2006). It has significant and various effects on marine ecosystems, negatively impacting the normal community structure of various species (Scheffer & Carpenter, 2003). Due to advances in transportation, significant population expansion, fast economic development, and rising geographic significance, the coastal regions are now home to vigorous human activity (Bera & Maiti, 2019; Konko *et al.*, 2020).

1.2 Coastal pollution

The World Health Organization defines coastal pollution as "the introduction of substances or energy into the marine environment, including estuaries, by man, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, an obstacle to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of the sea". The dynamic and vulnerable coastal-marine ecosystems are severely harmed by the concentration of human population worldwide, which frequently results in significant issues and social conflicts as a result of the loss of vital ecological services (de Andrés *et al.*, 2018). The majority of nations in the globe, including the United States, China, India, Britain, and more than 50 regions, have confronted a very significant dilemma in recent decades: the discharge of industrial effluent in coastal areas (Ma *et al.*, 2023).

Two-thirds of cities with a population of more than 2.5 million are situated close to tidal estuaries, and over half of the world's population resides within a 60 km radius of a coastline (Li *et al.*, 2019). The rapid economic expansion resulted in major changes in the biological environment of the coastal region (Miah *et al.*, 2023). The economic hubs of the coastal nations of the globe have moved to coastal regions since the 20th century (Sengupta *et al.*, 2023). The natural characteristics of coasts have been rapidly diminished, and their original production capacity and ecological function have altered significantly as a result of the development of numerous coastal projects and the rapid expansion of the area's economy (Bell *et al.*, 2016).

The ecosystems and biodiversity of coastal areas are being negatively impacted by the rising rate of pollution (Derraik, 2002). Coastal pollution has detrimental effects on environment that also affect human health and well-being, jeopardize food security, and threaten livelihoods (Carbery *et al.*, 2018; Hennessey & Sutinen, 2005; Williams *et al.*, 2016). The massive oil spills from the Exxon Valdez and Deepwater Horizon, as well as the increasing occurrence of hypoxic dead zones in the ocean as a result of eutrophication, are some of the most well-known instances of coastal pollution (Riechers *et al.*, 2021). The disappearance of famous ecosystems like coral reefs (Carpenter *et al.*, 2008) and seagrass meadows (Orth *et al.*, 2006) are accelerated by marine and coastal pollution.

Furthermore, biochemical processes and physical parameters are altered by climate change and ocean acidification, adding to the stress on marine and coastal ecosystems (Doney *et al.*, 2009; Kroeker *et al.*, 2013; Lu *et al.*, 2018). The amount of information about the features, methods, and measurement of coastal and marine pollution whether from point sources or non-point sources, chronic or discrete is growing exponentially (Horton, 2022; Lebreton *et al.*, 2017; Riechers *et al.*, 2021). The Sustainable Development Goals, which focus on life below water (SDG 14) and responsible consumption and production (SDG 12), are primarily accountable for an increase in awareness (UN, 2015).

1.3 Pathways of pollutants distribution in the coastal area

Pollution is primarily caused by human activities, and natural events such as floods and earthquakes are also contributing for it (Figure 1.2). It is not surprising that densely populated areas tend to be the most polluted. Different human societies contribute to pollution at varying levels, with industrial activities playing a significant role in the generation of physical and chemical pollutants. While pollutants are distributed throughout oceanic ecosystems via oceanic and atmospheric circulation, coastal areas are more heavily impacted by pollution compared to open-ocean environments (Beiras, 2018). The high concentration of human population, including major cities, near the coast contributes to coastal zones being more affected by pollution. Contaminants are mainly transported to the sea through freshwater inputs near the shore, and ocean margins act as effective filters for dissolved and particulate substances. Estuaries, in particular, serve as traps for riverine-transported materials that end up in estuarine sediments, capturing a large portion of land-based nutrients and trace elements transported by rivers and the atmosphere (Beiras, 2018).

Contaminant sources can be categorized as point sources or non-point sources based on their dispersion. This categorization is beneficial operationally because it is easier to reduce pollution from point sources compared to non-point sources. Point-source pollution can be mitigated by implementing new technologies and investing in wastewater treatment, while controlling discharges from diffuse sources is considerably more challenging (Henri *et al.*, 2020; Marais *et al.*, 2024). For instance, efforts to combat waterbody eutrophication caused by nutrient excess often focus on phosphates, originating from point sources like urban sewage carrying detergents, as opposed to nitrates, which primarily come from diffuse sources such as runoff waters contaminated by fertilizers used in agriculture (Manasa & Mehta, 2020).

The residence time of pollutants in tidal estuaries is significantly longer compared to rivers, leading to a decreased ability to dilute point discharges due to tidal influences (de Pablo *et al.*, 2022). An example of this can be seen in the Thames estuary, where the seaward flow speed decreases from over 20 km per day to just 2 km per day at the mouth, resulting in increased residence time due to upstream flow during flood tide (Clark, 2001). Sediment pollution in coastal zones is of greater significance than in deeper waters, as the benthic-pelagic coupling and resuspension characteristic of shallow environments may promote the recycling of contaminants from sediments, unlike in oceanic waters (Valiela, 2015). Coastal ecosystems, being highly productive, suffer from particularly harmful ecological and economic impacts of pollution. The neritic zone, extending from a low-tide level to a depth of approximately 200 m, is densely populated by benthic organisms due to the penetration of sunlight (Hedgpeth, 1957).

Human activities on land are the primary source of environmental contaminants, which are transported to the sea through three main routes: via the atmosphere, riverine input, or direct spillage into the sea (Windom, 1992). The entry of water from rivers, carrying pollutants from both urban and rural areas as well as liquid waste from sewage and industry, is the primary means by which dissolved and particulate contaminants are transported from land to sea. Estuaries, which are where rivers meet the sea, serve as filters that trap a large portion of the materials brought by the rivers, including contaminants (Durães *et al.*, 2018; Singh *et al.*, 2020). Coastal sediment globally serves as a major repository for contaminants. Key factors contributing to this include the precipitation of dissolved elements due to increased salinity, the formation of aggregates from colloids, and the settling of suspended matter as a result of reduced current speed and tidal dynamics near river mouths. Suspended particulate matter can settle due to the decrease in current velocity and processes associated with estuarine circulation and tidal dynamics (Grabemann & Krause, 1989).

Fine particles, such as clay and colloids, can form aggregates that sink faster due to flocculation. This is made possible by the positive ions in seawater neutralizing the negative charge on the surface of clay particles (Guézennec *et al.*, 1999). The introduction of contaminants into the atmosphere is significant for substances with low vapor pressure that evaporate from land sources, for gases and particles resulting from the burning of organic matter (OM), including fossil fuels and their trace metals, and for aerosolized pesticides and other products (Briffa *et al.*, 2020). Long-distance atmospheric processes are responsible for the presence of chemical pollutants even in uninhabited regions of the Earth. These contaminants can be washed onto the sea surface by rainfall. In areas with pollution, an oil slick on the water's surface creates a hydrophobic layer where organic compounds accumulate at concentrations much higher than those in the water below (Pokazeev *et al.*, 2021).

The sea can experience high local input of contaminants, such as deliberate dumping of waste, activities on oil platforms, or accidents involving oil tankers or other ships carrying hazardous substances (Freedman, 1995; Tornero & Hanke, 2016). The United States, the United Kingdom, and France conducted nuclear testing in the Pacific Ocean until 1996. Until the London Convention on the Prevention of Marine Pollution took effect in 1975, industrial and radioactive wastes were disposed of in the ocean depths. From 1949 to 1982, eight European countries dumped 140,000 T of radioactive waste 700 km from the northwest Iberian coast (Beiras, 2018). Marine dumping of dredged materials still occurs. The abandonment of non-degradable plastic fishing nets in the sea is an ongoing environmental concern (Spanier & Zviely, 2023). Other sources of direct pollution resulting from poor practices and navigation routines are more dispersed but may account for a significant portion of hydrocarbon or plastic input into the oceans (Beiras, 2018).

Coastal ecosystems are typically more polluted than oceanic waters due to population density and proximity to pollution sources. Pollution consequences are particularly significant in these productive ecosystems. Estuarine sediments accumulate and concentrate materials carried by rivers, including chemical pollutants (Häder *et al.*, 2020). The accumulation is attributed to increased salinity due to precipitation and reduced current speed and tidal dynamics due to sedimentation (Ganju, 2023; Mathew & Winterwerp, 2020). Some pollutants are not easily degraded by chemical or biological processes and can persist in the environment for years. Many of these pollutants also tend to accumulate in organisms and may cause toxicity. The environmental persistence and bioaccumulation aspects challenge the effectiveness of dilution as a strategy against pollution (Saravanan *et al.*, 2021; Yu *et al.*, 2024).

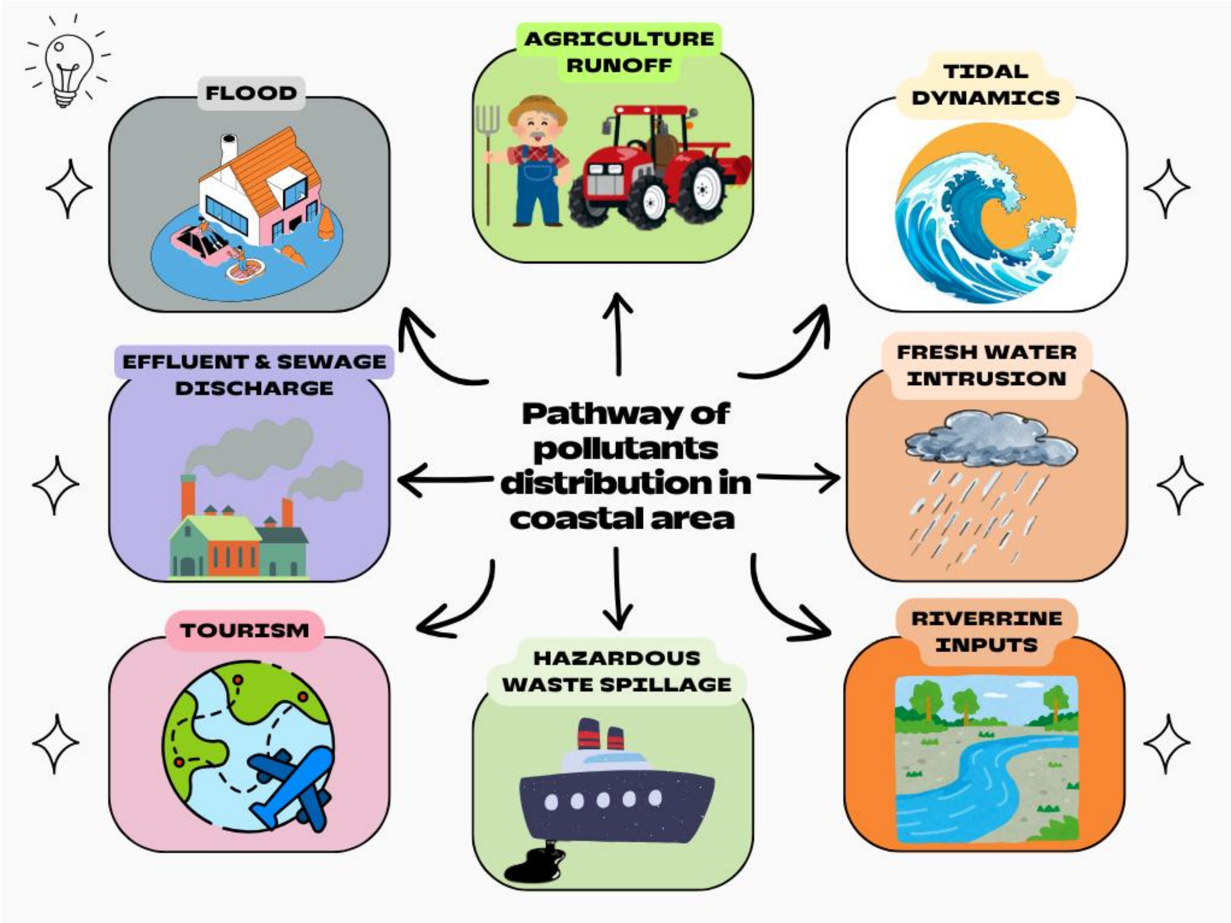

Figure 1.2 Different sources of pollutants introduction into the coastal area

1.4 Physico-chemical characteristics, heavy metals content of coastal water and sediment

Effluent discharges and human activities, such as overfishing, transportation, recreation, and tourism, pose a threat to the coast (Rajak *et al.*, 2024). The coastal organisms living in the marine environment are influenced by the various changes in the coastal areas. Coastal ecosystems experience numerous stresses that greatly reduce biodiversity (Bertness, 2007). Physico-chemical parameters significantly impact the distribution, reproduction, feeding, and other aspects of organisms in the coastal ecosystem (Lavanya *et al.*, 2024; Potter *et al.*, 2015). The high productivity of coastal ecosystems fosters a diverse range of marine flora and fauna (Levin *et al.*, 2001).

Changes in physico-chemical characteristics due to seasonal variation and human pressures affect the biotic elements (Dey *et al.*, 2021). These vulnerable environments are greatly affected by rapid urbanization and industrial growth. The dense human population in coastal watersheds contributes to environmental contamination (He & Silliman, 2019). Reference characteristics of the coastal environment are essential for effective management solutions. Comprehensive data collection programs for seawater physico-chemical parameters are crucial for understanding the effects of human activities on coastal environments (Gosai & Mankodi, 2024b). Stress factors related to health impact the habitats of aquatic environments and lead to a significant decrease in biodiversity. It is expected that aquatic ecosystems will lose more biodiversity and face more consequences in the future compared to terrestrial ecosystems (Martinez & Rusch, 2014).

Sediments act as a natural buffer and filtration system in aquatic environments and serve as both a habitat and a primary nutrient source for aquatic species (Gilley, 2005; Palmer *et al.*, 2000). The metabolic activities of bottom-dwelling cold-blooded animals contribute to marine production, and sediment deposits serve as an important habitat for them (Gage, 1978). Continuous accumulation of pollutants caused by biological and geological factors has been reported to harm the environment and creatures, resulting in decreased survival, growth, and offspring, as well as a decrease in species diversity (Ali *et al.*, 2021; Car *et al.*, 2024). Factors such as flow rate, substance input and movement, and sedimentation affect aquatic systems. Sediment analysis is becoming increasingly important in analyzing the overall ecology of a water body and discussing the hydrochemistry of water quality, in addition to the traditional water sample analysis that has been used for many years (Förstner & Wittmann, 1981).

Pollutants can remain stored in sediments for extended periods based on their substance and the physical, chemical, and biological properties of the substrate (Calmano *et al.*, 1996). Understanding sediment parameters is essential for studying coastal dynamics and other geomorphological behaviours of coast. Sand size distribution studies can provide insights into the origin, depositional environment, and movement history. Moreover, sand-size analysis is a crucial tool for differentiating facies and habitats (Masselink *et al.*, 2014). Assessing the concentration of heavy metals in sediment is crucial in understanding the extent of metal pollution (Siddiqui & Pandey, 2019). The distribution of heavy metals in solution has been widely recognized as a major factor affecting the geochemical behaviour, transport, and biological effects of these elements in natural waters. Sediments are often referred to as a 'Trace Element Trap' as they tend to accumulate almost all heavy metals that enter the aquatic environment (Gaonkar & Matta, 2019).

Assessing the environment for potential heavy metal contamination is extremely important. Heavy metals are essential for the survival of all organisms, as they are involved in various metabolic processes. Organisms require metals like copper (Cu), zinc (Zn), cobalt (Co), nickel (Ni), chromium (Cr), manganese (Mn), and cadmium (Cd) within safe limits. However, the risk arises from their tendency to accumulate within organisms, leading to increased chemical concentrations. If these concentrations surpass safe limits, they can become toxic. Even at low concentrations, heavy metals such as lead (Pb), mercury (Hg), and arsenic (Ar) can be harmful (Al-Kahtany *et al.*, 2023; El-Sorogy *et al.*, 2024).

Coastal sediments, located nearest to land in marine areas, have a vital function in the aquatic ecosystem. Nevertheless, they have elevated concentrations of heavy metals in comparison to other aquatic environments. These sediments not only transport pollutants but also have the potential to cause additional pollution due to their substantial involvement in chemical and biological processes (Gosai & Mankodi, 2024a). Suspended particles scavenge large concentrations of pollutants, leading to their retention in estuarine sediments. Sediment samples are frequently used to monitor heavy metal pollution in coastal areas. Analysis of sediment often reveals evidence of heavy metal contamination, and numerous studies have been conducted on the distribution of heavy metals in water and sediments in Indian regions (Anbuselvan *et al.*, 2018; Gaonkar & Matta, 2019; Gosai & Mankodi, 2024a, 2024b; Sundaramanickam *et al.*, 2016; Venkatramanan *et al.*, 2014).

1.5 Coastal microorganisms

The role of microorganisms in ecosystems is fundamental and indispensable for the biogeochemical cycles that support life on Earth. Microbial communities exhibit significant diversity and complexity, influenced by a wide array of factors such as soil properties and the types of plants present in the environment (Madsen, 2011). These factors serve as primary determinants of the structure of microbial communities, shaping their composition and function. Microorganisms are essential for various processes including the decomposition of organic matter in soil, the facilitation of sulfate reduction, sulfide/sulfur oxidation, iron reduction, nitrification, pollutant degradation, and the improvement of soil structure and ecosystem stability (Singh, 2024). Moreover, coastal areas present unique ecological challenges, featuring distinct nutrient and salinity gradients resulting from interactions between freshwater and seawater (Xin *et al.*, 2022). These conditions have a profound impact on the composition of soil microbial communities, ultimately influencing the structure and function of coastal water and sediments (Reed & Martiny, 2012).

1.6 Environmental potential of microorganism

The vast number of microbial species and the diversity of species found in this natural environment make studying microorganisms a difficult undertaking for microbiologists. The species composition and spatiotemporal dynamics of soil microbial communities have been linked to plant species, human interferences, and habitat features in previous research (Eddie *et al.*, 2010). Functionally varied microbial communities play a role in the biogeochemical transformation of components like nitrogen (N) and carbon (C) (Yang *et al.*, 2022). These biological processes mainly include carbon formation and degradation, carbon fixation and nitrogen metabolism, methane metabolism, and exogenous biodegradation and metabolism (Mohapatra *et al.*, 2021). Biogeochemical processes such as the carbon and nitrogen cycle processes rely heavily on microorganisms to retain chemical contaminants including organic pollutants and excessive nutrients (Horton *et al.*, 2019).

Although they are so sensitive to changes in their surroundings, microorganisms can be a perfect indicator for keeping an eye on the environment. Variations in microbial ecology over a brief time imply that they may act as precursors to sea level rise (Chambers *et al.*, 2011). Microorganisms have gained popularity as pollutant bioremediation alternatives due to their affordability and environmental friendliness (Macaulay, 2015). Toluene, naphthalene, chloroalkanes, and chlorinated alkanes can all be broken down by the bacterial community found in the sediments of the Mexican coastal zone, but it is not very good at breaking down aromatics, fluorobenzoates, or xylenes (Reyes-Sosa *et al.*, 2018). Salt marshes around the Gulf of Mexico exhibit an increase in the relative abundance of hydrocarbon-degrading bacteria (*Proteobacteria*, *Actinobacteria*, and *Bacteroidetes*) in hydrocarbon-contaminated sediments. *Proteobacteria*, *Bacteroidetes*, *Firmicutes*, and C*hloroflexi* bacteria that break down polycyclic aromatic hydrocarbons increase in mangroves when the Jiulongjiang estuary is contaminated with these compounds (Beazley *et al.*, 2012).

1.7 Lacunae of study area

The existing scientific research on the spatial-temporal variation of physico-chemical characteristics and heavy metal assessment of coastal water and sediment in the study area is currently inadequate. Furthermore, there is limited documentation on the seasonal microbial study conducted on the coastal sediment in the region, specifically within the Bhavnagar coast located in the Gulf of Khambhat, Gujarat, India. The findings and insights from this study are crucial as they will establish a fundamental reference point for administrative bodies and the local community. Their utilization will play a pivotal role in the preservation and sustainable management of the coastal ecosystems within the Bhavnagar coast, Gulf of Khambhat, Gujarat, India.

1.8 Aim and Objective

The study aims to assess the pollution level of coastal water and sediment and the microbial community structure present in coastal sediments in these conditions of Bhavnagar coast, Gulf of Khambhat, Gujarat, India.

To achieve this aim, the following objectives are set:

(1) Spatio-temporal assessment of physico-chemical characteristics and heavy metals content of coastal surface water. Seasonal data to be collected to observe seasonal trends in physico-chemical characteristics and heavy metal content of coastal water. The data also be compared with reported data from different locations of the present study.

(2) Spatio-temporal assessment of physico-chemical characteristics and heavy metals content of coastal surface sediment. Seasonal data to be collected to observe seasonal trends in physico-chemical characteristics and heavy metal content in coastal sediment. The data also be compared with reported data from different locations of the present study.

(3) Spatio-temporal assessment of microbial diversity of coastal surface sediment. Seasonal microbial data to be collected to observe seasonal trends in microbial diversity.