INVESTIGATING SOURCE APPORTIONMENT AND ECOLOGICAL RISK ASSESSMENT OF MICROPLASTIC POLLUTION IN THE SURFACE WATERS OF PINANG RIVER AND KERIAN RIVER USING SPATIAL ANALYSIS

MUHAMMAD IZZUL FAHMI BIN MOHD ROSLI

UNIVERSITI SAINS MALAYSIA

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by

MUHAMMAD IZZUL FAHMI BIN MOHD ROSLI

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LIST OF SYMBOLS

°C	Temperature in Degree Celcius
%	Percentage
<	Smaller than
>	Higher than
≤	Equal or Smaller than
≥	Equal or Bigger than
ρ	Correlation coefficient
y	Component score
b	Component loading
x	Measured value of the variable
i	Component number
j	Sample number
m	Total number of variables

LIST OF ABBREVIATIONS

MPs	Microplastics
FTIR	Fourier Transform Infrared Spectroscopy
RQ	Risk Quotient
MEC	Measured Environmental Concentration
PNEC	Predicted No-Effect Concentration
PCA	Principal Component Analysis
PCs	Principal Component
TSS	Total Suspended Solids
DO	Dissolved Oxygen
WQI	Water Quality Index
CDC	Conductivity
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
ABS	Acrylonitrile Butadiene Styrene
POPs	Persistent Organic Pollutants
USEPA	United State Environmental Protection Agency
DOE	Department of Environment
TDS	Total Dissolved Solids
WQPs	Water Quality Parameters
NH_3	Unionized Ammonia
PO_4	Phosphate
NO_3	Nitrate
KMO	Kaiser-Meyer-Olkin
VF	Variance Factor

LIST OF APPENDICES

KAJIAN PENENTUAN PUNCA DAN PENILAIAN RISIKO EKOLOGI PENCEMARAN MIKROPLASTIK DI PERMUKAAN AIR SUNGAI PINANG DAN SUNGAI KERIAN MENGGUNAKAN ANALISIS SPATIAL

ABSTRAK

Pencemaran mikroplastik dalam ekosistem air tawar merupakan isu alam sekitar yang semakin mendapat perhatian disebabkan sifatnya yang tahan lama, tersebar luas, dan berisiko terhadap ekologi. Kajian ini menyiasat sumber, taburan, dan risiko ekologi mikroplastik di permukaan air Sungai Pinang (Balik Pulau) dan Sungai Kerian (Nibong Tebal), Malaysia. Dua sungai tersebut terdedah kepada pelbagai guna tanah termasuk pertanian, akuakultur, dan pembangunan bandar. Kajian ini menggabungkan sejarah data kualiti air (2017–2021), pengukuran in-situ, stereomikroskopi, pengecaman polimer menggunakan FTIR, serta penilaian risiko ekologi melalui kaedah Risk Quotient (RQ). Untuk mengenal pasti sumber pencemaran yang berpotensi, data sekunder kualiti air dianalisis menggunakan Analisis Komponen Utama (AKU), yang menunjukkan bahawa kedua-dua sungai lebih banyak dipengaruhi oleh sumber pencemaran yang meresap seperti aliran limpahan pertanian, sisa akuakultur, dan buangan domestik. Persampelan mikroplastik dijalankan di dua belas stesen (enam bagi setiap sungai), dan sampel diproses melalui penapisan, pengecaman meggunakan stereomikroskop, serta analisis FTIR. Keputusan menunjukkan peningkatan bilangan mikroplastik di bahagian hilir, dengan gentian (contohnya nilon) mendominasi di Sungai Pinang dan serpihan (contohnya ABS, polimer nitril) di Sungai Kerian. Corak ini selari dengan guna tanah sekeliling sumber tekstil dan akuakultur di Sungai Pinang serta plastik pertanian dan sisa bandar di Sungai Kerian. Jenis polimer dikesan secara konsisten dalam tiga musim pensampelan, menunjukkan pencemaran kronik dan bukan bersifat bermusim. Risiko ekologi dinilai melalui pengiraan nilai RQ bagi setiap stesen dengan membandingkan kepekatan mikroplastik yang diukur dengan Konsentrasi Tanpa Kesan Teramal (PNEC) (PNEC). Nilai RQ menunjukkan risiko ekologi sederhana di kedua-dua sungai, terutama di SP4–SP5 (Pinang) dan SK4–SK5 (Kerian), yang terletak berhampiran kawasan guna tanah berimpak tinggi. Tambahan pula, ketika persampelan ketiga yang bertepatan dengan Monsun Timur Laut mencatatkan nilai risiko tertinggi, menunjukkan pengaruh bermusim terhadap kemasukan mikroplastik ke sistem air tawar. Kajian ini telah menghasilkan penilaian komprehensif terhadap pencemaran mikroplastik di Sungai Pinang dan Sungai Kerian serta menyumbang data tempatan yang signifikan kepada kekurangan kajian berkaitan di Malaysia. Penemuan ini menekankan keperluan pengurusan lembangan sungai yang disasarkan, amalan kawalan sisa yang lebih baik, dan strategi mitigasi bermusim. Kajian lanjut disarankan melibatkan analisis sedimen, biota, dan pemantauan jangka panjang bagi memahami kesan mikroplastik terhadap ekosistem dan kesihatan manusia secara menyeluruh.

INVESTIGATING SOURCE APPORTIONMENT AND ECOLOGICAL RISK ASSESSMENT OF MICROPLASTIC POLLUTION IN THE SURFACE WATERS OF PINANG RIVER AND KERIAN RIVER USING SPATIAL ANALYSIS

ABSTRACT

Microplastic pollution in freshwater ecosystems is an emerging environmental concern due to its persistence, widespread distribution, and ecological risks. This study investigates the sources, distribution, and ecological risks of microplastics in the surface waters of the Pinang River (Balik Pulau) and Kerian River (Nibong Tebal), Malaysia. These two rivers are subjected to varied land uses, including agriculture, aquaculture, and urban development. The study integrates historical water quality data (2017–2021), in-situ measurements, stereomicroscopy, FTIR polymer identification, and ecological risk assessment through the Risk Quotient (RQ) method. To identify potential pollution sources, secondary water quality data were analyzed using Principal Component Analysis (PCA), revealing that both rivers are predominantly impacted by diffuse sources such as agricultural runoff, aquaculture effluents, and domestic discharges. Microplastic sampling was conducted across twelve stations (six per river), and samples were processed through filtration, stereomicroscopic identification, and FTIR analysis. Results indicated that microplastic abundance increased downstream, with fibres (e.g., nylon) dominating in Pinang River and fragments (e.g., ABS, nitrile polymers) prevailing in Kerian River. These patterns correlate with surrounding land using textile-related and aquaculture sources in Pinang River and agricultural plastics and urban waste in Kerian River. Polymer types were consistently detected across three sampling seasons, suggesting chronic, non-seasonal contamination. Ecological risk was assessed by calculating RQ values at each station, comparing measured microplastic concentrations against a predicted no-effect concentration (PNEC). RQ values indicated moderate ecological risk in both rivers, particularly at SP4–SP5 (Pinang River) and SK4–SK5 (Kerian River), stations adjacent to high-impact land uses. Notably, the third sampling period, coinciding with the Northeast Monsoon, recorded the highest risk values, highlighting seasonal influence on microplastic inputs. This study offers a comprehensive assessment of freshwater microplastic pollution in the Pinang River and Kerian River, contributing valuable local data to the limited body of research on Malaysian rivers. The findings emphasize the need for targeted watershed management, improved waste control practices, and seasonal mitigation strategies, while also supporting future policies to protect aquatic ecosystems. Further studies involving sediments, biota, and long-term ecological monitoring are recommended to better understand the full extent of microplastic impacts on ecosystems and human health.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In recent years, microplastic pollution has gained widespread attention as a major environmental problem affecting aquatic ecosystems. These small plastic particles are usually smaller than 5 mm and are found in freshwater and marine environments around the world (Borriello et al., 2023; Tirkey & Upadhyay, 2021). Its persistence in the environment, combined with its ability to accumulate and disperse through water systems, poses a growing challenge for environmental surveillance and management (Li et al., 2022; Pastorino et al., 2021).

Although global research focuses mainly on marine environments, attention is now focusing on freshwater systems, particularly rivers, as important pathways through which microplastics travel from land sources to the ocean (Everaert et al., 2020; Sheela et al., 2021). Rivers are particularly vulnerable due to their exposure to various anthropogenic activities. Microplastics enter these systems through several means, including surface drainage, domestic and industrial discharges, agricultural drainage and aquaculture waste (Jin et al., 2022; Kim et al., 2021). Once in the aquatic environment, it poses a direct threat to aquatic organisms, not only by intake and physical harm, but also by transferring toxic substances to the food network (Wang et al., 2021).

In Southeast Asia, rapid urbanization and land use changes are changing landscapes, and rivers are increasingly contaminated by plastic (Babel et al., 2022; Ng et al., 2023). Malaysia is experiencing increasing concern about the presence of microplastics in its freshwater bodies. While conventional water quality assessments, such as the Water Quality Index (WQI), provide useful information about chemical and biological pollutants, they do not identify microplastics, suggesting a critical gap in current monitoring approaches. Recent studies have reported the presence of microplastics in several Malaysian rivers, but many systems are still underrepresented in scientific literature.

The Pinang and Kerian rivers are two systems that deserve further study. These rivers are located in important areas of development and are surrounded by agricultural and aquaculture areas, both of which are well-known contributors to microplastic pollution. Activities such as the cultivation of brackish water cages, the cultivation of ponds and the use of plastic agricultural equipment increase the likelihood of plastic materials entering nearby water bodies (Blanco et al., 2018; Chen et al., 2021; Jin et al., 2022). Over time exposure to environmental stress factors such as sunlight and water flow fragments these materials into microplastics that persist and accumulate in the aquatic environment.

These economic activities support local livelihoods and food production but also create unresolved environmental pressures. The discharge of plastic waste from agricultural and aquaculture infrastructures, combined with inefficient waste management systems, creates several points of entry for microplastics into river systems (Chen et al., 2021; Corradini et al., 2019; Qi et al., 2023). Furthermore, the physical and chemical properties of microplastics allow them to remain suspended in water or stabilize in sediments under local hydrodynamic conditions (Mao et al., 2021; Razeghi et al., 2021). Floating on the surface is particularly concerned, as it is easily absorbed by aquatic species, causing internal damage, changing food behaviour, and potentially affecting growth.

Despite improvements in water quality throughout Malaysia, microplastic pollution remains an emerging and unregulated problem. As plastic pollution spreads, its impacts on aquatic ecosystems, food security and public health require specific scientific research. The lack of local data on the distribution of microplastics, particularly in river systems such as Pinang and Kerian, limits the ability of policy makers and environmental managers to deal with the problem effectively.

This study aims to investigate the sources, spatial distribution, and ecological risks of microplastic pollution in the surface waters of the Pinang and Kerian Rivers. By exploring the relationship between land use activities, aquaculture expansion, and microplastic contamination, this research seeks to contribute to a deeper understanding of microplastic behaviour in freshwater systems and support the development of targeted strategies for sustainable river management in Malaysia.

1.2 Problem Statement

Microplastic pollution has emerged as a global environmental concern due to its persistence, mobility, and potential impacts on aquatic ecosystems and human health (Chen et al., 2019; Schwabl et al., 2019). Rivers, as both sinks and transport pathways, play a critical role in transferring microplastics from land-based sources to downstream environments. While marine environments have been extensively studied, freshwater ecosystems particularly in Malaysia remain underexplored with respect to microplastic contamination (Zaki et al., 2024).

In Malaysia, long-term water quality monitoring data are available for many rivers, and multivariate techniques such as Principal Component Analysis (PCA) are widely applied to identify pollution sources and assess water quality status (Arman et al., 2025; Camara et al., 2020). However, such approaches have not been extensively applied to explore potential relationships between water quality conditions and microplastic abundance. This gap limits understanding of how pollution sources and environmental parameters may indirectly influence the occurrence of microplastics in rivers such as the Pinang and Kerian.

Beyond water quality, the occurrence, distribution, and physical characteristics of microplastics in Malaysian rivers remain poorly understood. Most local studies have concentrated on coastal and marine environments, leaving freshwater systems underexamined. The Pinang River in Balik Pulau and the Kerian River in Nibong Tebal are particularly vulnerable, as they are exposed to urbanization, tourism, agriculture, and aquaculture all of which are potential contributors to microplastic inputs (Akhtar et al., 2022; Khairun et al., 2012). However, comprehensive assessments that integrate stereomicroscopy for morphological analysis and Fourier Transform Infrared Spectroscopy (FTIR) for polymer identification are still lacking.

Finally, the ecological risks of microplastics in Malaysian freshwater systems remain unassessed. Although the Risk Quotient (RQ) method, based on Predicted No-Effect Concentration (PNEC), has been applied in coastal and estuarine zones (Zainuddin et al., 2022), its application in rivers is infrequent. Current research indicates that the ecological risk quotient for microplastics in most Malaysian aquatic environments is generally low, while localized hotspots could increase risks. Understanding these links is vital to the development of targeted strategies for preserving freshwater biodiversity and supporting the sustainable management of important river systems such as the Pinang and Kerian rivers.

1.3 Objective of the Study

The study aims to investigate microplastic pollution in the surface water of Pinang River, Balik Pulau, and Kerian River, Nibong Tebal through the following specific objectives:

1. To identify possible pollution sources based on water quality parameter from 2017 – 2021 in Pinang River and Kerian River using Principal Component Analysis (PCA).
2. To determine the presence, distribution, morphological and structure of microplastics in the surface water of Pinang River, Balik Pulau and Kerian River, Nibong Tebal through stereomicroscopy observation and Fourier Transform Infrared Spectroscopy (FTIR) analysis.
3. To evaluate microplastic pollution risk in the surface water of Pinang River, Balik Pulau and Kerian River, Nibong Tebal using the Risk Quotient (RQ) approach based on Predicted No-Effect Concentration (PNEC).

1.4 Significance of Study

Microplastics pose a significant risk to both the environment and living organisms. This proposed research can provide invaluable insight into the extent of microplastic pollution in selected rivers in Penang and its potential implications.

Meanwhile, Malaysia's government is implementing "Malaysia's Roadmap Towards Zero Single-Use Plastics 2018-2030" to reduce the plastic usage and improve the environment. This study indirectly supports these efforts by providing a deeper understanding of microplastics and narrowing the knowledge gap regarding the effects of microplastic pollution, which has been a growing concern annually. This will be achieved through the data obtained, aligning with existing research.

Furthermore, this research will explore the influence of land use activities and water quality parameters on the abundance and distribution of microplastics in the surface waters of Pinang River and Kerian River. Land use patterns such as urban development, agriculture, and aquaculture are potential contributors to microplastic input into freshwater systems. In parallel, water quality parameters including pH, turbidity, and temperature will be analyzed to understand their role in influencing the behavior, transport, and persistence of microplastics in these aquatic environments. By examining these interrelated factors, the study aims to provide a comprehensive understanding of how both anthropogenic activities and environmental conditions shape microplastic contamination in riverine ecosystems. Ultimately, the findings of this research are expected to contribute valuable insights to the scientific community, support evidence-based environmental management strategies, and promote the protection of ecosystem and public health.

1.5 Hypothesis and Research Questions

1. What are the possible sources of water pollution in the surface water of Pinang River and Kerian River based on the analysis of water quality parameters from 2017 to 2021 using Principal Component Analysis (PCA)?
2. What are the levels of abundance, spatial distribution, morphological and structural characteristics of microplastics present in the surface waters of Pinang River and Kerian River through stereomicroscopy observation and Fourier Transform Infrared Spectroscopy (FTIR) analysis?
3. What is the microplastic pollution risk posed by the presence of microplastics in the surface waters of Pinang River and Kerian River using the Risk Quotient (RQ) approach based on Predicted No-Effect Concentration (PNEC), and how does this risk vary between the two study sites?

1.6 Scope of Study

This study examines microplastic pollution of the surface waters of the Pinang River in Balik Pulau and the Kerian River in Nibong Tebal, Pulau Pinang, Malaysia. It aims to identify potential sources of pollution based on water quality parameters recorded between 2017 and 2021, determine the presence, distribution and morphological characteristics of microplastics and assess the ecological risks associated with microplastic contamination of these rivers. The research involves the analysis of long-term water quality data, the field sampling of microplastics, and the laboratory analysis of microplastic types, shapes, sizes, and colours. The ecological risk is assessed using the risk quotient (RQ) approach. The sampling was carried out during two monsoon seasons and one inter-monsoon period to capture potential temporal variations in the presence and quality of microplastics.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As water pollution continues to affect ecosystems globally, one of the most pressing pollutants has become plastics, particularly microplastics, which have significant effects over time on human health and aquatic life. In this chapter, literature review is divided into three sections. Section 2.1 provides an overview of water pollution globally and its relevance to Malaysian water bodies. Section 2.2 discusses Principal Component Analysis (PCA) in water quality and pollution source identification. Section 2.3 describes the prevalence of plastic pollution. Meanwhile, the prevalence of microplastics will be discussed in Section 2.4. This section also will discuss techniques for microplastics water sampling, detection and polymer identification.

2.2 Water Pollution

Globally, water pollution is driven by various sources. This issue is particularly pronounced in countries like Malaysia, where industrialization, urbanization, and agriculture contribute significantly to water contamination. A major worldwide environmental issue that affects ecosystems and human health extensively is water pollution. This problem occurs when dangerous materials seep into rivers, lakes, seas, and groundwater, degrading the quality of the water and upsetting sensitive aquatic ecosystems. Water pollution comes from a wide range of sources, including urban waste, agricultural runoff, and industrial discharges (Noor & Khan, 2023). These pollutants not only endanger the well-being of aquatic life, but also compromise the availability of safe drinking water, recreational opportunities, and agricultural productivity on which human society depends (Häder et al., 2020). Surface water level, typically defined as the top 0–20 cm of the water column, is the most directly influenced by atmospheric conditions, sunlight, and surface turbulence (Egessa et al., 2020). This layer plays a critical role in pollution dynamics, as contaminants from industrial emissions, agricultural runoff, and urban waste tend to accumulate in the uppermost portion of the water column, increasing the risk of exposure to aquatic organisms and the broader ecosystem.

In Malaysia, the issue of water pollution is particularly pressing due to the country's rapid industrialization, urban expansion, and agricultural growth (Camara et al., 2019; Garba et al., 2021). Major rivers and coastal areas in Malaysia are experiencing an increasing level of contamination, posing significant environmental challenges. In urban areas, improper waste disposal practices and inadequate sewage treatment facilities contribute to the pollution of water bodies (Chin et al., 2020; Mustafa et al., 2020). Furthermore, agricultural activities introduce additional pollutants through the runoff of fertilizers and pesticides (Camara et al., 2019; Elfikrie et al., 2020). The burden is further exacerbated by industrial operations that release various chemicals and pollutants into the environment (Aslam et al., 2021; Salam et al., 2019). Effectively addressing these issues necessitates a comprehensive understanding of the sources and consequences of water pollution, as well as the development and implementation of robust management strategies.

2.2.1 Water Pollution Factors

The causes that contribute to water pollution are numerous and interconnected, and each one leads to a decline in water quality. Land use changes, especially those associated with urbanization and agriculture, have a significant impact on water pollution (Wijesiri et al., 2018). This process involves converting natural landscapes into urban habitats, resulting in a substantial increase in impermeable surfaces like roads and buildings. Industrial effluents, agricultural runoff, and urbanization are all interlinked industrial processes that are intensified by urban sprawl, while urbanization exacerbates agricultural runoff by converting natural landscapes into impermeable surfaces. As a result, the runoff from these surfaces is directed straight into rivers and lakes, carrying pollutants such as oil, heavy metals, and sediments from various sources (Ni et al., 2021). Industrial effluents are another prominent source of water pollution. Manufacturing facilities and mills often release harmful byproducts into water bodies, including heavy metals, chemicals, and untreated waste (Shrestha et al., 2021). These contaminants can pose a threat to aquatic life and have long-term effects on the ecosystem and human health. Inadequate treatment infrastructure and weak regulatory monitoring exacerbate the problem, with serious consequences for marine ecosystems and human wellbeing.

Agricultural runoff, particularly in areas with intensive fertilizer and pesticide use, is a major cause of water pollution. The leakage of these substances into groundwater or their transportation through surface runoff leads to high nutrient concentrations in aquatic systems (Klein et al., 2023). This excessive nutrient supply results in eutrophication, characterized by algal blooms and a decrease in oxygen availability in the water, thereby endangering aquatic life (Duré et al., 2021). Additionally, urbanization has a significant impact on water contamination by the expansion of metropolitan areas leads to an increase in wastewater and stormwater runoff, often exceeding the capacity of existing waste management systems (Falkenberg et al., 2018). Inadequate sewage treatment and disposal procedures contaminate water sources, exacerbating concerns about water pollution.

2.2.2 Water Quality Indicators

Identification and analysis of indicators of water quality is essential in fully comprehending water pollution to point out the presence and impact of pollutants. To assess the impact of pollutants such as industrial effluents and agricultural runoff, various water quality indicators are used. These indicators help evaluate the extent of contamination and guide mitigation efforts. Among several indicators, one of them is Chemical Oxygen Demand (COD), whose analysis was necessary to establish whether there was sufficient oxygen for the oxidation of the organic pollutants present in the aquatic environment. Higher values of COD indicate the presence of high amounts of organic pollutants, perhaps because of wastewater discharges or some industrial discharges (Sharma et al., 2021). The other important parameter is Biochemical Oxygen Demand (BOD), which makes up the measure of the amount of oxygen required to be consumed by harmful aquatic microorganisms for breaking down organic matter. High values of BOD mean high contents of organic matter and may correspond to the condition where the aquatic environment becomes oxygen depleted (Zhong et al., 2021).

Nitrates and phosphates are the basic components to which other sources are attached, mainly land runoff. Too high a concentration of these nutrients can result in eutrophication, which increases the growth of harmful algal blooms and reduces the general state of aquatic systems (Wurtsbaugh et al., 2019). Other serious issues include heavy metals like lead, mercury, and cadmium. Industrial processes are the major source for all these metals, and thus they pose significant toxicity to aquatic life and humans (Singh et al., 2023).

The pH is one of the most important parameters, as it measures acidity or alkalinity, a property of water that is directly linked to the ability of the medium to host living organisms. Therefore, changes in pH are indicator phenomena of pollution caused by acid rain and diverse types of industrial effluents can pose risks to aquatic life and ecosystems (Qu & Han, 2021). In this way, monitoring these changes is important in the evaluation of water quality and assessment of pollution effects, and it's crucial to design effective management strategies.

2.2.3 Water Pollution in Malaysia

Like many countries facing rapid urbanization, Malaysia is experiencing escalating water pollution due to both industrial and agricultural activities. Notably, incidents such as the Kim Kim River pollution highlight the urgent need for effective regulatory measures. The investigation of specific cases of water pollution in Malaysia allows one to gain a better understanding of the degree and complexity of this phenomenon. One case that stands out is the Kim Kim River pollution case of 2019. In this shocking incident, toxic waste had been illegally dumped in the river, causing widespread pollution (Ibrahim et al., 2021). Besides affecting water quality, the entry of dangerous elements had very negative health effects on communities nearby. The situation plainly showed the dangers of industrial pollution and highlighted the pressing need for stricter enforcement of regulatory laws.

Another significant example is the water crisis in Selangor River in 2009. It was caused by industrial waste being disposed of into one of Malaysia's major rivers and led to a massive disruption of water supply for a population of several million people (Abidin et al., 2018). The effect was sudden and significant, thus clearly demonstrating that water pollution directly affects the populace. It was a significant lesson and a good reminder that effective measures in handling pollution and waste management are urgently needed.

Nevertheless, these examples mentioned do not represent isolated cases but are part of a broader global trend in which industrialization and rapid urbanization combine with deficient waste infrastructure to contaminate life-giving water. Moreover, local conditions above all, regulatory arrangements and their effective enforcement also strongly mediate the impact of such situations. It is an issue that can be addressed by implementing measures that control regulations, develop enhanced methods of managing waste, and raise awareness among people regarding water pollution in Malaysia.

2.3 Statistical Approaches in Environmental Pollution Studies

Environmental datasets, such as water quality measurements, often consist of numerous interrelated variables including physicochemical parameters, nutrients, and trace pollutants. These variables are typically correlated, making it challenging to identify the dominant factors controlling pollution patterns. Multivariate statistical techniques have therefore become essential tools for environmental research, as they allow the integration, simplification, and interpretation of large datasets (Nguyen et al., 2021). Among these techniques, principal component analysis (PCA), cluster analysis (CA), and discriminant analysis (DA) are commonly employed in water quality studies. Cluster analysis is often used to classify monitoring sites with similar water characteristics, while discriminant analysis evaluates the influence of specific parameters on spatial or temporal patterns. PCA, however, is particularly powerful for identifying the underlying structure of datasets and recognizing pollution sources (Nguyen et al., 2021; Sikakwe et al., 2020).

2.3.1 Principal Component Analysis (PCA) in Water Quality and Pollution Source Identification

Principal component analysis (PCA) is a statistical method that transforms a large set of correlated variables into a smaller number of uncorrelated variables known as principal components. Each principal component represents a linear combination of the original variables and explains a certain proportion of the total variance in the dataset (Greenacre et al., 2022). By reducing dimensionality, PCA highlights the most influential parameters and uncovers patterns that may not be apparent through conventional univariate analysis.

In water quality studies, PCA has been widely used to extract key factors governing river and lake pollution. For example, Zhang et al. (2022) applied PCA to river water quality data in Min River, China and identified nutrient enrichment from agriculture, sewage effluents and industrial discharge as dominant pollution sources. Similarly, Llamas et al. (2023) used PCA in Guadiaro River, Spain to distinguish between natural, agricultural, and urban contributions to river contamination. In Malaysia, several studies have also adopted PCA to analyze water quality datasets, highlighting agricultural runoff, aquaculture effluents, and urban waste as critical drivers of river pollution (Camara et al., 2019; Khairudin et al., 2022).

The application of PCA is particularly valuable for source identification because each principal component can be interpreted in terms of potential pollution origins. For instance, high loadings of nutrients such as nitrate and phosphate are typically associated with agricultural activities, while strong associations of biochemical oxygen demand (BOD) and ammonium may indicate domestic wastewater inputs. Likewise, elevated concentrations of heavy metals or industrial by-products may point to industrial discharges (Zhou et al., 2020).

By reducing data complexity and linking parameter patterns to likely sources, PCA enables researchers and policymakers to better understand spatial dynamic. In this study, PCA is applied to both historical (2017–2021) from the Pinang River and Kerian River. The aim is to identify the dominant parameters influencing water quality variability and to infer possible pollution sources related to agriculture, aquaculture, and urban activities. The inclusion of PCA therefore supports Objective 1 by providing a robust statistical framework to trace the origins of pollution and understand the interactions between water quality indicators and land use activities in the studied river systems.

2.4 Plastic Pollution

As water pollution worsens globally, plastics have emerged as one of the most persistent and problematic pollutants. This is particularly concerning in aquatic environments, where plastic waste accumulates and is slowly broken down into harmful microplastics. Plastic pollution has emerged as a significant environmental concern, with far-reaching and intricate implications for ecosystems and human well-being on a global scale. According to Kosior & Crescenzi (2020) globally estimates, more than 8 million tons of plastic waste are deposited into the Earth's oceans annually, leading to a progressive buildup of plastic debris in marine habitats. This form of pollution poses a grave threat to marine organisms, as they are prone to ingesting or becoming entangled in plastic remnants, resulting in severe harm or mortality. Moreover, the degradation of plastics into microplastics further compounds the issue, as these particles are consumed by various life forms, thereby potentially infiltrating the food chain and posing risks to human health (Borriello et al., 2023).

Plastic pollution is a pressing issue in Malaysia due to its status as a major contributor to marine plastic debris in Southeast Asia. The high prevalence of plastic waste in aquatic environments may be associated with factors such as high consumption rates, insufficient waste collection methods, and widespread dependence on single-use plastics (Fauziah et al., 2021). The approach to tackling plastic pollution in Malaysia entails an integrated framework of regulatory interventions, public awareness initiatives, and technological innovations aimed at reducing plastic waste and improving waste management practices.

2.4.1 Sources and Pathways of Plastics into Hydrosphere

The sources and pathways by which plastic pollution occurs are complex and varied, reflecting both large volumes and lack of effective control of plastics. Aquatic systems are directly exposed to plastic waste from direct disposal into the water, litter or poor waste disposal and ineffective waste management systems (Vaid et al., 2021). Besides that, landfills and litter may be intercepted by atmospheric mechanisms or hydrological ones that distribute contamination to aquatic environments (van Emmerik et al., 2023) .Marine activities associated with fishing and shipping generate plastic pollution through abandoned gear, lost nets, and ropes that can be ingested by marine species or entangle them, which generally adds to the plastic load in the ocean (Nelms et al., 2021).

Runoff from both urban and rural areas acts as a significant transport mechanism for plastics into aquatic systems (van Emmerik et al., 2023). Hence, plastics are fragmented into smaller sized particles, further increasing their transport potential through the stormwater system to larger-sized aquatic systems (Onink et al., 2022). The runoff of plastics is enhanced by the increase of cities, farming activities, and land clearance, especially where the ground is densely filled with impermeable surfaces (Zhang et al., 2022). For example, agricultural fields make use of plastic products such as plastic mulch films, which are prone to fragmentation and subsequent transportation into nearby bodies of water. Land use changes that reduce plant cover and increase surface runoff amplify the transport of plastics to aquatic systems (Zhang et al., 2020).

Plastic pollution, mainly microplastics entering the aquatic ecosystem, is one of the significant determinants in water quality (Caruso, 2019). They have the potential to absorb and carry harmful pollutants such as heavy metals and Persistent Organic Pollutants (POPs) into the food chain, which imparts risks not only to aquatic life but also to human health (Huang et al., 2021; Tang et al., 2021). The presence of plastics in the aquatic environment significantly changes water physical and chemical properties, such as oxygen levels and pH values, which in turn deteriorates water quality and eventually disrupts aquatic ecosystems (Vázquez & Rahman, 2021). Moreover, atmospheric deposition is a means by which microplastics are conveyed over long distances through wind and atmospheric processes, eventually depositing into aquatic environments-a process that underlines the global dimensions of the issue and associated challenges in tackling it (Chen et al., 2021).

2.4.2 Management and Mitigation Strategies for Plastic Pollution

Plastic pollution control and mitigation are addressed through various initiatives operated at the international and national levels. Internationally, treaties such as the Basel Convention foster controls on the transboundary movements of plastic wastes, supported by environmentally sound management of hazardous materials (Ahmad Khan, 2020). Scores of countries have introduced bans on the use of certain plastics and set targets for reducing the volume of single-use plastics consumed, to aid the transition to less harmful alternatives.

The Malaysian national effort for reducing plastic waste is manifold by plastic bag bans, improved waste handling processes, and awareness among people (Chen et al., 2021). The government has tried to frame policies that would reduce the use of plastics and involve recycling. More locally operated schemes clear the pollution from within the community. It is vital because technology also assists in such a way that it develops plastic materials that easily deteriorate or uses complex techniques that manage plastic waste.

In summary, plastic pollution requires a solution that incorporates regulatory frameworks, techno-innovative solutions, and public participation in the mitigation process. A better understanding of the sources, transport processes, and impacts of plastic pollution will be required to develop and implement effective management strategies that reduce plastic waste to protect environmental and human health.

2.5 Microplastics Pollution

As plastics degrade over time, they fragment into smaller particles known as microplastics, which are now recognized as a major environmental threat. Microplastics, tiny plastic particles less than 5mm in diameter, are a growing environmental concern due to their widespread presence and impact on both terrestrial and aquatic life (Baho et al., 2021). They are categorized into primary and secondary microplastics. Primary microplastics are intentionally manufactured small particles found in products like exfoliating scrubs, facial cleansers, toothpastes, and synthetic textiles such as clothing and carpets clothing (Dalla Fontana et al., 2020). These particles are produced at a sub-millimetre size, making them difficult to filter out in wastewater treatment plants and leading to their rapid discharge into aquatic ecosystems.

In contrast, secondary microplastics result from the degradation of larger plastic items due to physical, chemical, or biological factors like weathering, UV radiation, and microbial digestion (El Hadri et al., 2020). These microplastics enter the environment through sources such as plastic litter, synthetic fibers from clothing, and rubber particles from tire wear. Both primary and secondary microplastics pose significant risks to aquatic organisms and can enter the food chain, carrying pollutants like heavy metals and persistent organic pollutants (Tang et al., 2021).

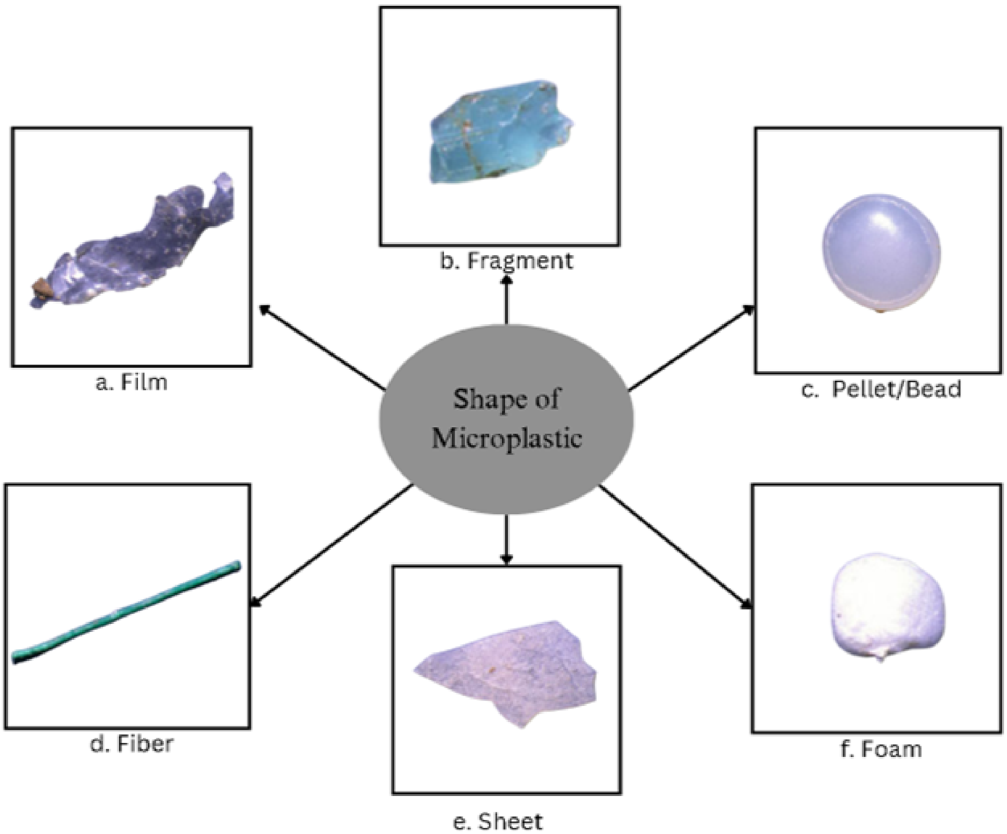

Figure 2.1 Shape of microplastics found in rivers and estuaries

The shapes of microplastics, such as elongated fibers, irregular fragments, pellet, sheet, foam and thin film-like forms are different from one another (Lozano et al., 2021). These various shapes arise from sources like breaking down larger plastics, wearing out synthetic materials and creating primary microplastics in personal hygiene products. Figure 2.1 shows the six commons shape of microplastics found in river and estuarine based on the study from (Wu et al., 2018). The kind of shape exhibited by microplastics determines their interaction with the environment such as while fibers might entangle aquatic organisms, spherical beads can easily be swallowed (Mammo et al., 2020; Wang et al., 2020).

Table 2.1 provides an overview of the different forms of microplastics present across many rivers in Southeast Asia. The studies that have been included in this table offer insights into the shape of microplastic present at each location, which serves only to draw further scrutiny upon the severity of plastic contamination in such waterways. A range of intriguing microplastic morphologies present in Southeast Asian rivers, including microbeads, filaments, fragments, fibers, films, monofilaments, foam, pellets, and spherules as described in Table 2.1 taken from Rosli et al. (2024) study. Such diversity reflects the differences in sources and pathways through which microplastics enter the water bodies. The shapes of microplastics are related to locally practiced activities, population density, waste management, and proximity to pollution sources. It underscores how urgent the need for an improvement in the existing waste management and pollution mitigation strategies is in the worst-hit areas, underlining the omnipresence of microplastic contamination and pointing out the need for regional mediation. It allows us, by considering the different varieties and configurations of microplastics, to better comprehend their sources and dispersion and possible effects on aquatic ecosystems and, consequently, to be able to design effective interventions for this pervasive issue.

Table 2.1 Shape of Microplastic Evidence in the Rivers

Location	Shape of Microplastics	References
Kuap River, Maong River and Sarawak River, Sarawak	Microbead, filament, fragment, fiber, film	(Jiménez-Skrzypek et al., 2021)
Dungun River, Terengganu	Fragment and fiber	(Yang Hwi et al., 2020)
Langat and Kelantan River	Fragment and fiber	(Anuar et al., 2023)
Brantas River, Indonesia	Fragment, fiber, film, and pellet	(Buwono et al., 2021)
Citarum River, Indonesia	Fragment, fiber, film, monofilament and foam	(Sembiring et al., 2020)
Surabaya River, Indonesia	Film, fragment, fiber, foam, and pellet	(Lestari et al., 2020)
Ciwalengke River, Indonesia	Fragment and fiber	(Alam et al., 2019)
Chao Phraya River, Thailand	Fragments, pellets, films, and fiber.	(Ta & Babel, 2020)
Chi River Basin, Thailand	Fiber, fragment, pellet and foam	(Thamsenanupap et al., 2022)
Tapi-Phumduang River and Bandon Bay, Thailand	Fibers, spherules, or fragments	(Chinfak et al., 2021)

Based on Jiménez-Skrzypek et al. (2021) in Sarawak, Malaysia, a variety of microplastic types, such as microbeads, filaments, fragments, fibers, and films, have been identified in the Kuap River, Maong River, and Sarawak River. Research conducted on the Sarawak River indicates that anthropogenic activities play a significant role in determining the concentrations of microplastic contamination, a condition further exacerbated by the river's proximity to waste disposal sites (Johnson et al., 2020). The Dungun River in Terengganu, Malaysia, is predominantly composed of fragments and fibers (Yang Hwi et al., 2020). In an empirical study, Yang Hwi et al. (2020) assessed the sampling sites of the Dungun River and demonstrated the notable impacts of local activities on the river's ecological environment. The Dungun River serves as a primary site for fishery catchment near the South China Sea and has been adversely affected by the increase in human activities. This study seeks to investigate the intensified human impacts resulting from local traditions, aiming to provide new insights into current ecological relationships in the area. Additionally, the Langat and Kelantan Rivers were selected for research due to the high population densities in those areas and the potential presence of microplastics resulting from human activities (Anuar et al., 2023). For instance, the Langat River catchment area in Selangor, Malaysia, serves as a vital source of water supply for over 2 million people in the surrounding area.

Microplastics primarily consists of synthetic polymer substances, such as polyethylene, polypropylene, and polyester. Table 2.2 from Rosli et al. (2024) shows polymer characteristics and uses. Polyethylene is commonly used in packaging applications, including plastic bags and bottles, due to its durability and remarkable flexibility. Polypropylene can be found in products like food containers and textiles, as it is resistant to chemical degradation and has a high melting point. Polyester is widely utilized in clothing and textiles due to its strength, anti-wrinkle properties, and elasticity. Microplastics vary in size, shape, and chemical composition, resulting in unpredictable interactions with natural environments and organisms. Consequently, their ability to sorb contaminants, such as heavy metals or persistent organic pollutants, differs from one another.

Table 2.2 Polymer Characteristics and Uses

Type of polymers	Common uses	Characteristics	References
Polyethylene (PE)	Packaging, plastic bags, bottles, toys and household containers	Lightweight, resistant to moisture, and chemicals	(Zhou et al., 2020)
Polypropylene (PP)	Food containers, bottle caps, straws and packaging films	Tough and resistant to heat,	(Zhang et al., 2023)
Polyvinyl Chloride (PVC)	Pipes, vinyl flooring, medical tubing, and packaging materials	Strong, durable, and resistant to chemicals	(An et al., 2020)
Polystyrene (PS)	Disposable cutlery, insulation and packaging foam	Lightweight and easily molded	(Pilevar et al., 2019)
Polyethylene Terephthalate (PET)	Beverage bottles, food packaging and textiles	Strong, lightweight, and commonly used for single-use products	(Djapovic et al., 2021)
Nylon (Polyamide)	Fishing nets, ropes and synthetic clothing	Strong, durable, and flexible	(Cywar et al., 2022)
Polyurethane (PU)	Foams, coatings, adhesives and sealants	Versatile, used in both rigid and flexible forms	(Somarathna et al., 2018)
Polycarbonate (PC)	CDs, DVDs, safety glasses, water bottles, and electronic housings	Strong, transparent, and impact-resistant	(Ueda, 2004)
Cellulose Acetate (CA)	Cigarette filters, textiles, film base photographic films, and eyeglass frames	Biodegradable under specific conditions	(Mondal & Alam, 2013)
Acrylonitrile Butadiene Styrene (ABS)	Automotive parts, toys, electronic housings and piping	Strong, lightweight, and impact-resistant	(Dundar et al., 2021)
Polytetrafluoroethylene (PTFE)	Non-stick coatings, gaskets, seals and electrical insulation	Highly resistant to heat, chemicals, and friction	(Dhanumalayan & Joshi, 2018)
Poly (methyl methacrylate) (PMMA or acrylic)	Signs, displays, skylights, lenses and aquariums	Strong, transparent, and weather-resistant.	(Sansul et al., 2023)
Ethylene Vinyl Acetate (EVA)	Footwear, adhesives, sports gear, and packaging	Flexible, durable, and resistant to UV radiation	(Schneider et al., 2017)

2.5.1 Occurrence of Microplastics Pollution

Microplastics as pollutants which are usually tiny, persistent and often described invisible under this descriptor can disrupt ecological balance and they may also become part of food webs or cause problems to human beings' well-being (Geyer et al., 2017; UNEP, 2018). Based on Luo et al. (2019) show that microplastics abound in oceans, coastal areas and fresh waters among others. According to an estimate, plastics weigh around 25,000 tons globally in seas (Lebreton et al., 2017). Consequently, microplastics have been identified in biota taken from surface water, sediments across various types of aquatic systems that are indicative of their wide-spread occurrence (Law & Thompson, 2014). According to research, high concentrations of microplastics have been discovered in such places as the Great Pacific Garbage Patch while its presence has also been recorded in far-flung unspoiled locations such as the Arctic and Antarctic regions (Peeken et al., 2018). This is an indication that aquatic environments everywhere on the planet are polluted with these tiny plastic particles called microplastics.

Microplastics have also been found in terrestrial environments like soils, farmland, and waste treatment plants. While research on terrestrial ecosystems and microplastics is limited compared to aquatic ecosystems, recent studies have shown that microplastic concentrations in soil samples are high especially in areas where human beings live and work closely together usually referred to as urban centers or agricultural regions (Bläsing & Amelung, 2018). These tiny plastic particles contaminate land due to different things such as the application of sewage sludge, littering or atmospheric deposition (Corradini et al., 2019). Though there is an increasing amount of literature on their effects, their destiny and function within