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Examining Soil Microplastics: Prevalence and Consequences Across Varied Land Use Contexts

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Abstract

In an extensive exploration of microplastics within soil environments, our study aims to investigate the presence, spread, and ecological impact of microplastics in soil, focusing on Makassar City, Indonesia. Using a Sinher binocular digital microscope, we visually examined soil samples in Petri dishes, measuring microplastic sizes with Image-J software. Fourier-transform infrared (FTIR) spectroscopy was also employed for additional identification and analysis of polymer compositions. Our research uncovered a widespread presence of microplastics across diverse soil types and land uses, including residential, fishpond, agricultural, landfill, coastal, and bareland areas. The concentration of these microplastics was found to be between 16.6 to 21.9 particles/gram, showing consistency across most land uses, with some variations in coastal areas. We noted a significant variety in microplastic forms, predominantly fragments and films, across the different land uses. A wide range of colors was observed, including blue, green, red, and transparent. Polyethylene (PE) and polypropylene (PP) were identified as the predominant polymers. Our study highlights the non-uniform distribution of microplastics in soil, suggesting potential significant impacts on soil organisms and the wider ecosystem. These findings underscore the critical need for more comprehensive research on the ecological implications of microplastics in soil environments.

Keywords: Microplastics; Soil; Land Use; Polymer; Soil Environment; Pollution.

1. Introduction

The examination of microplastics in diverse land-use contexts assumes paramount importance in the contemporary era, primarily attributed to the far-reaching and profound ecological and human health implications associated with these diminutive plastic particles [1]. Microplastics, defined as plastic fragments measuring less than 5 mm in diameter [2], have pervaded terrestrial ecosystems on a global scale, bearing testament to the pervasive nature of plastic pollution. An intricate understanding of the presence and spatial distribution of microplastics is of paramount significance, as it serves as a foundational prerequisite for the formulation of efficacious mitigation strategies and policy interventions aimed at ameliorating the escalating global plastic pollution crisis [3]. Notably, urban areas have emerged as focal points of

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microplastic pollution, manifesting elevated concentrations in locales characterized by high population density and industrial activity [4]. This underscores the pivotal role of urban planning and waste management strategies in abating the encroachment of microplastics into the environment. Extensive prior investigations have probed the prevalence of microplastics in agricultural soils, thereby illuminating the potential hazards attendant to their incorporation into these substrates, which can detrimentally impact soil health and potentially ingress the food chain [5, 6].

Microplastics have garnered notable scholarly attention in recent years, primarily due to their recognized potential for instigating adverse ecological consequences within terrestrial ecosystems. Within these terrestrial ecosystems, microplastics have been found to induce alterations in soil properties, disruptions in nutrient cycling dynamics, and deleterious effects on plant growth and microbial communities, as evidenced by recent studies [7, 8]. Such perturbations in terrestrial environments can precipitate cascading repercussions, ultimately impacting the structural and functional integrity of ecosystems, with consequential implications for the wildlife populations that depend on these ecosystems for habitat and sustenance. For instance, empirical investigations have unveiled that microplastics, upon ingestion by earthworms, give rise to physiological stress and provoke modifications in their feeding behaviors, thereby exemplifying the extent of the ecological perturbations attributable to microplastic contaminants [9]. Furthermore, it is imperative to underscore that the transport of microplastics from aquatic ecosystems to terrestrial environments is facilitated by diverse mechanisms, as elucidated in recent research endeavors [10]. This cross-environmental transfer highlights the necessity for rigorous and comprehensive examinations, encompassing diverse land use contexts, to thoroughly comprehend the prevalence and ramifications of microplastics.

The study of microplastics within a variety of contexts related to land use is crucially important when considering assessments of human health. This urgency is echoed by several scholarly investigations, which have emphasized the necessity of examining the subtle ways through which these microscopic plastic particles might enter our food chain, thereby posing potential risks to human health [11–13]. In a pivotal study conducted by Schwabl et al. [14], the presence of microplastics was identified in human stool samples, offering indisputable evidence that humans inadvertently ingest and possibly absorb these minute particles. Moreover, there is a well-documented correlation between microplastics and the attachment of harmful chemical substances to their surfaces. This connection stirs significant concern regarding the possibility that when humans consume contaminated food or water, they may also inadvertently ingest these dangerous compounds [15]. Therefore, undertaking a broad and meticulous exploration of microplastics within diverse land-use settings is not only vital for gaining a deeper understanding of the ecological impacts but is also indispensable for evaluating the hidden health risks that these particles might pose to the general population. Through such a comprehensive study, we will not only garner a nuanced understanding of microplastics' environmental impacts but will also be better positioned to navigate and mitigate the concealed health risks associated with them, ensuring a safer and more informed future for all.

A thorough examination of microplastics, covering both their prevalence and ensuing impacts, is vitally important, given their significant implications for sustainable development and their emergence as a prominent ecological issue intricately linked to sustainability [16]. Addressing the issue of microplastics aligns closely with several Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water) and SDG 15 (Life on Land), by targeting marine and terrestrial ecosystems [17]. Furthermore, tackling microplastic pollution contributes to SDG 3 (Good Health and Well-being) by safeguarding human health from potential contaminants, as well as to SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) by promoting responsible consumption and mitigating climate impacts associated with plastic production [18]. To support these SDGs, concerted efforts are needed, including interdisciplinary research, policy interventions, public awareness campaigns, and innovative solutions for plastic waste management, emphasizing the interconnectedness of microplastic research with broader sustainability objectives. These initiatives highlight the crucial link between microplastics research and broader sustainability goals. Recognizing this vital focus, the primary objective of this research is to study the prevalence of microplastics in terrestrial ecosystems and their relationship with land use. Particularly, the study seeks to determine the extent of microplastic infiltration in these areas and identify the underlying causative factors.

A significant research gap exists in the study of microplastics in soil, necessitating focused investigation to address critical knowledge deficits in this domain. While earlier studies predominantly investigated the presence of microplastics in aquatic systems [19], recent studies have shifted their focus towards terrestrial soil, particularly with the fact that microplastic deposition in soil is estimated to be 4 to 23 times higher than in marine environments [20], causing a growing concern. This is substantiated by various studies identifying human activities as significant contributors to microplastic contamination in soil. Such activities encompass littering [21], the utilization of plastic mulching [22], soil amendment applications [23], irrigation with sewage water [24], waste disposal practices [25], and the application of fertilizer coatings [26]. Furthermore, environmental mediums like runoff and air transmission play a role in soil microplastic contamination as well [27]. Given the considerable uncertainty surrounding the composition, volume, and concentration of microplastic particles infiltrating terrestrial soil, there is corresponding ambiguity regarding their impact on the soil [28], particularly concerning different land uses. The variability in land use, from agricultural to industrial, further complicates the interaction between microplastics and soil, making it challenging to ascertain their overall impact on soil health, structure, and function [29]. The intricate dynamics of land use, soil composition, and microplastic pollution necessitate comprehensive, site-specific investigations. This is imperative not only to delineate the scope and degree of soil contamination by microplastics but also to elucidate the nuanced relationship between soil use and the extent of contamination and impact. Conducting on-site, detailed investigations is essential to unveiling the complex interplay of these variables, thereby providing a foundation for effective strategies to mitigate the impact of microplastics on terrestrial environments.

According to the World Bank [30], Indonesia annually generates an alarming 7.8 million tons of plastic waste, out of which a substantial 4.9 million tons are mismanaged, leading to critical environmental and public health concerns. This mismanaged waste includes uncollected plastics, plastics disposed of in open dumpsites, and those leaking from inadequately managed landfills [30, 31]. Given the severity and scale of the problem, there is an urgent need to formulate effective waste management strategies and policies to mitigate the adverse impacts of mismanaged plastic waste in Indonesia.

In the context of Eastern Indonesia, South Sulawesi emerges as a paramount economic epicenter, evidenced by its substantial populace, totaling approximately 8.8 million, and its significant contribution to the region's economy [32]. The capital city of this province, Makassar, is particularly noteworthy, accounting for 47.2% of South Sulawesi's economic production. This economic prowess has predominantly been propelled by sectors such as agriculture, forestry, and fisheries, which collectively contribute 21.3% to the province's economy [33]. The confluence of escalated population growth and industrial advancement in Makassar presages an escalation in environmental challenges, particularly the intensification of microplastic pollution [3]. Prior research endeavors have primarily concentrated on the detection and distribution of microplastics within aquatic and coastal zones in Makassar [34-37]. A solitary investigation has addressed the contamination of terrestrial ecosystems by microplastics, with a specific focus on the potential transference from landfill sites to dug wells [38]. Nevertheless, there is a pronounced dearth of comprehensive studies examining the pervasiveness of microplastics across various land use categories within Makassar. The current understanding of the extent of microplastic pollution in this locale remains incomplete. Given this backdrop, our investigation aims to fill these critical knowledge gaps. Our study intends to systematically explore the prevalence and implications of microplastic pollution across diverse land use settings in Makassar. This research not only seeks to augment the existing body of knowledge within this specific urban context but also aspires to contribute significantly to the global discourse on microplastic pollution. Understanding the distribution and impact of microplastics across varying land use contexts is crucial, as it allows for a comprehensive assessment of the pathways and mechanisms through which these pollutants infiltrate different ecosystems, ranging from urban centers to agricultural lands, thereby informing targeted and effective mitigation strategies.

2. Literature Review

2.1. Plastic Pollution: The Current Global Landscape and Its Problem

Over recent years, the scientific community has acknowledged plastic pollution as a principal environmental threat [39]. Plastics have been increasingly identified as substantial environmental pollutants [40]. In 2021, the global production of plastics reached a staggering 390.7 million tons, growing annually at the rate of 5.8 percent since 2009, following a consistent upward production trend since the 1960s [41]. This increment in production inevitably results in an increasing amount of plastic ending up in the environment annually. Due to the durability and persistence of these materials, plastics continue to reside in the environment indefinitely [42]. Rochman & Hoellein [43] elucidated the interactions of plastics ranging from the lithosphere to the atmosphere and from the hydrosphere to the atmosphere. Analogous to other chemical elements, plastic waste undergoes a biogeochemical cycle. Depending on their degradation rates, plastics participate in cycles involving the atmosphere, terrestrial systems (lithosphere), and aquatic systems (hydrosphere), all of which are intricately interconnected.

2.2. Microplastic Pollution in The Soil Environment

Investigations into the presence of microplastics in soil are still in their initial stages worldwide. While the phenomenon of plastic pollution has been thoroughly examined since the early 1970s, such explorations have predominantly been confined to aquatic settings, primarily oceans. It was not until the recent decade that the scope of this research expanded to include terrestrial ecosystems, as highlighted by a study by Sun et al. [44]. Crucially, findings by researchers, including a significant study by Rodrigues et al. [45], have unveiled that plastics contaminating the environment do not remain in a fixed location. Instead, these materials are dynamic, moving, and circulating across various ecosystems. This implies a constant transfer of microplastics between different environmental segments, from water bodies to the land, and vice versa. The process through which microplastics find their way into terrestrial settings, or land-based environments, is depicted in Figure 1. This illustration serves as a visual representation to aid in understanding the movement and introduction of microplastics into the soil and broader land environments.

In accordance with Figure 1, Lu et al. [46] emphasized the intimate connection between the distribution and formation of soil aggregates and the surrounding ecological conditions. The development and dispersal of these aggregates are invariably tethered to the local environmental context. Notably, human activities and the prevalent vegetation types exert considerable influence on this dynamic, subsequently molding the underlying biological processes and facilitating or impeding the movement and circulation within the soil. This interaction is crucial as it ultimately affects the soil's health and functionality [47].

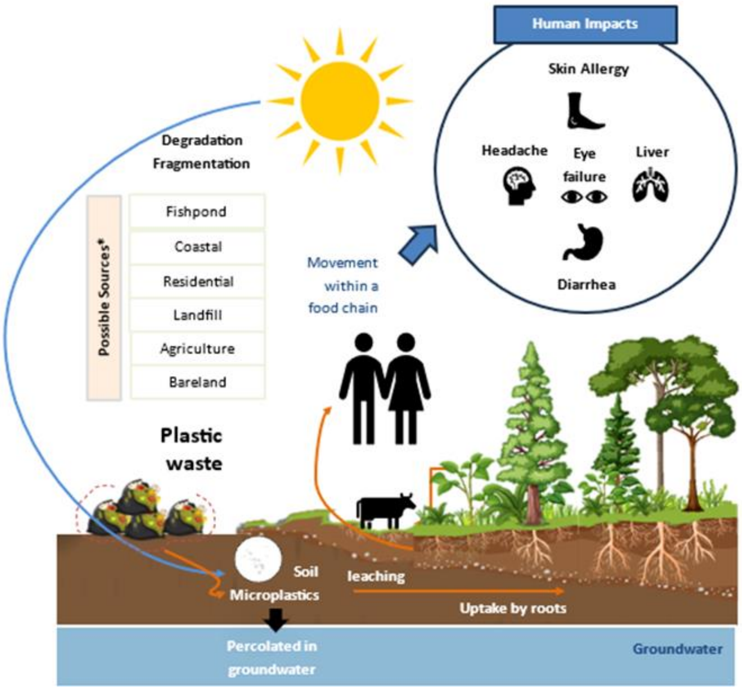


Figure 1. Microplastics Pathway to Soil Environment (Modified from [21, 48])

Further, Xu et al. [49] delineated how microplastics, upon entering the soil, become a quasi-permanent component of the environment. Once entrenched in the soil, these microplastics don't merely lie inert; they engage actively with the surroundings. They may accumulate over time, act as sponges absorbing various contaminants, or traverse through the soil matrix. This movement through the soil is not simplistic or unidirectional; it is a multistage process with several nuanced levels of transportation. For instance, at the cellular level, specific enzymes play a pivotal role in breaking down plastics into smaller, more manageable pieces [50, 51]. Simultaneously, at the organismal level, invertebrates inadvertently facilitate the exposure and perhaps even the redistribution of microplastics during their digestive processes [52]. These microplastics are not broken down completely and can be integrated into the food chain, increasing the potential for and degree of microplastic accumulation [53]. As these materials pass through the food chain, the probability of accumulation increases, posing potential risks to various organisms and the ecosystem at large [54].

Persistent presence of plastic waste leads to its accumulation in substantial concentrations, whereupon it undergoes degradation into minuscule pieces, a process expedited by UV radiation [55]. These microplastics once embedded in the soil, exert a tangible impact on the food chain dynamics. As elucidated by Gao et al. [56], plants are susceptible to absorbing microplastics, which infiltrate the soil and contaminate the groundwater. This absorption occurs as the contaminated water percolates through the soil and is subsequently taken up by the plants.

Once microplastics enter the vegetative components of the food chain, their presence becomes pervasive. Animals feeding on these contaminated plants inadvertently ingest microplastics [57]. Given that these animals, in turn, are consumed by humans, there is a consequent and inevitable transfer of microplastics to the human body. This accumulation within the human physiological system is not benign and has been linked to deleterious health effects, as documented by Issac & Kandasubramanian [48] and Zhang et al. [58]. These researchers have meticulously outlined the health risks associated with plastics, emphasizing that these risks are prevalent throughout various stages of plastics' life cycle.

Given the position of humans atop the food chain, and with food being significantly tainted by microplastics, the transfer of these tiny plastic particles to humans is not only plausible but highly likely. Moreover, other scholarly contributions have shed light on the negative implications microplastics pose to the vitality and growth of soil biota [59, 60]. Interestingly, research by Selonen et al. [61] underscored the vital role soil invertebrates play in the transportation of microplastics. According to their findings, these invertebrates can ingest microplastics, thereby incorporating them into the terrestrial food web. This cycle of ingestion and transfer eventually leads to the accumulation of microplastics, which, in turn, might precipitate detrimental effects on various facets of the environment, reverberating through the entire food chain and ecosystem.

Ajith et al. [62] put forth a significant assertion suggesting that microplastics discovered within marine ecosystems globally have their origins primarily linked to terrestrial sources. This perspective is not isolated, as it garners support from an array of other research endeavors in the field. A salient example can be observed in the work conducted by Zhang et al. [58], which throws light on the intricate relationships between surface soil aggregate composition, stability, and specific patterns of land use. According to their findings, distinct land-use patterns have a discernible impact on both the composition and stability of soil aggregates. These aggregates are not merely structural components of soil but serve a function vital to the ecosystem; they act as carriers of nutrients within the soil milieu, providing necessary sustenance to microorganisms thriving in this habitat. Such a role is indispensable, as it directly influences the soil structure, consequently affecting the availability and accessibility of nutrients within the soil environment [61, 63]. A study articulated by Yang et al. [21], alongside the insights provided by Kumar et al. [64], unveils the unsettling reality of persistent soil contamination caused by microplastics. These microplastics, derived from an array of different sources, continuously infiltrate the soil, emphasizing the urgency to comprehend the mechanisms underlying the dispersion of microplastics. Understanding these mechanisms is not merely an academic endeavor but a pressing environmental imperative as it significantly informs the efforts aimed at mitigating the extensive contamination and pollution propagated by microplastics. The collective findings underscore the need for increased awareness and intervention to address the widespread dispersion and consequential impacts of microplastics originating from diverse terrestrial sources.

Researchers in the field of soil science have meticulously compiled data, shedding light on the primary routes facilitating the ingress of microplastics into soil environments. There is compelling evidence pointing toward soil amendments, specifically compost [65] and sludge [66, 67], as vehicles transporting and dispersing microplastics. These amendments, commonly used in agricultural practices, inadvertently channel microplastics from urban waste disposal facilities to expansive tracts of agricultural land. In the scholarly landscape, there has been a discernible concentration of research efforts zeroing in on agricultural soils. This focus is attributed to the pervasive practice of over-fertilization, where phosphate fertilizers are used excessively in agricultural settings [66]. Intriguingly, there is a noticeable correlation unfolding between the increased presence of microplastics in soil and elevated phosphorus levels, drawing a direct link to the use of these phosphate fertilizers. Additionally, it is plausible that the farming community in certain regions may have consistently relied on compost for their agricultural needs. Empirical studies, one notably conducted by Cambier et al. [68], have brought to light that the practice of repeated compost application to soil does not come without repercussions. Continuous and repeated application cycles result in the gradual yet steady accumulation of microplastics in the soil, leading to heightened concentrations of these environmentally detrimental particles.

Drawing from an extensive review of prior research, a definitive presence of microplastics within various soil types has been unequivocally determined and established. Table 1 meticulously enumerates the data from different countries, each pinpointing the detection of microplastics in soils under assorted land use categorizations. The historical research has predominantly articulated findings regarding the concentration levels of these microplastics, the specific types of polymers identified, and the conjectured sources introducing microplastics into the soils. For soils associated with fishponds and aquaculture land uses, microplastic concentrations vary considerably, ranging from a minimal 0.46 to an excess of 112 particles per kilogram. Soils in landfill areas exhibit slightly elevated microplastic concentrations, with a range extending from 2.7 to a substantial 863 particles per kilogram.

Coastal regions also demonstrate diverse concentration levels, spanning from 12 to 590 particles per kilogram. Agricultural soils presented a wider range, with microplastic concentrations fluctuating between 5 and an alarming 1200 particles per kilogram. Notably, residential areas, which were the focus of a singular study in Turkey, displayed a surprising and unprecedented microplastic concentration of 3378 particles per kilogram. These findings collectively highlight the ubiquity and variability of microplastic concentrations in soils across different land-use types, each influenced by a distinct set of factors and sources contributing to the overall microplastic load in the environment. Understanding these variations is crucial for developing effective strategies for mitigating microplastic pollution and protecting soil health in these vulnerable areas. Despite the comprehensive data on microplastic presence in various soil types across different land uses, the research gap lies in the lack of a unified, comparative analysis of these findings. Specifically, there's a need to systematically compare and contrast microplastic concentrations and types across different land uses like fishponds, landfills, coastal regions, and agricultural soils. Additionally, the research predominantly focuses on quantifying microplastic levels and identifying polymer types, leaving a gap in understanding the direct and indirect ecological impacts of these microplastics on soil health and related ecosystems. Moreover, while the data shows significant variability in microplastic concentrations across land uses, there is a scarcity of research exploring the underlying reasons for these variations, such as specific local practices or environmental factors. Filling these gaps is essential for developing targeted and effective environmental management strategies to address microplastic pollution in soils.

Table 1. Microplastics Prevalence in Varying Land Use

Location	Land-Use Type	Concentration	Polymer Types	Potential Source	Reference
Hungary	Fishponds, Fresh Water	3.52-32.05 particles/m^3 (water) 0.46-1.62 particles/kg (sediment)	PP, PE (water) Polystyrene (sediment)	Uptake by organism	Bordos et al. (2019) [69]
Neijing River, China	Aquaculture Ponds	372 particles/m^3 (June) 429 particles/m^3 (December)	-	Water system	Xiong et a. (2022) [70]
Jakarta Bay, Indonesia	Aquaculture Ponds	111.7±13.2 particles/kg	PE, PP, PET, Polystyrene, Polyamide, PVC	Pipe, water system	Priscilla et al. (2020) [71]
North Carolina, USA	Landfill	382 particles/L (raw) 2.7 particles/L (treated)	LDPE, HDPE, Polystyrene, PP, PVC, PET	Degradation and fragmentation of plastic waste	Kabir et al. (2023) [72]
Finland, Norway, Iceland, China	Landfill	291 particles/L	PE, PA, PVC, PET, PU, HDPE, LDPE	Waste, chemicals	Silva et al. (2021) [73]
Iran	Landfill (soil)	863 ± 681 particles/kg	LDPE, PP, PS	Degradation of plastic waste	Shirazi et al. (2023) [74]
Singapore	Coastal Areas	12-62.7 particles/kg	PA, PE, PP, PVC	-	Hazimah & Obbard (2014) [75]
Northern Coast, Taiwan	Coastal Areas	54.8 particles/kg	ABS, PE, PP, PS	Disposed Waste	Kunz et al. (2016) [76]
North Mississippi, USA	Beach	590±360 particles/kg	PE, Polyamide, PMMA, PET, PC, PP	Degradation of plastics	Gao et al. (2022) [77]
Chile	Agriculture	1200 particles/kg	-	Plastic mulching	Büks & Kaupenjohann (2020) [78]
Chile	Agriculture	306±360 particles/kg (cropland) 184±266 particles/kg (pastures)	Acrylates, PU, PE, EVA, PP, Nitrile Rubber, PS, CPE, PET, Polyamide, Polylactic Acid	Agriculture activities, mining, roadways, and urban environment	Corradini et al. (2021) [79]
Germany	Agriculture	30-50 mg/kg dry weight of agricultural area	-	Sewage sludge, compost	Henseler et al. (2022) [80]
China	Agriculture	263 – 571 particles/kg	PE, PP, PET, rayon, acrylic, polyamide	Agro-ecosystem	Zhou et al. (2020) [81]
China	Agriculture	4.94 – 252.70 particles/kg 37.32 particles/kg (average)	PP	Road Input	Cao et al. (2021) [82]
Turkey	Residential	3378 particles/kg	-	Anthropogenic activities	Tunali et al. (2022) [83]

ABS: Acrylonitrile Butadiene Styrene, **CPE**: Chlorinated Polyethylene, **EVA**: Ethylene-vinyl acetate, **HDPE**: High Density Polyethylene, **LDPE**: Low Density Polyethylene, **PA**: Polyacetylene, **PC**: Polycarbonate, **PE**: Polyethylene, **PET**: Polyethlene Terephthalate, **PMMA**: Poly(Methyl Methacrylate), **PP**: Polypropylene, **PS**: Polystyrene, **PU**: Polyurethane, **PVC**: Polyvinyl Chloride, **PVP**: Polyvinylpyrrolidone.

The polymers most commonly identified in these studies were Polyethylene (PE), Polystyrene (PS), and Polypropylene (PP), each contributing to the microplastic contamination within these diverse land use scenarios. The introduction and accumulation of microplastics in these soils are influenced by various sources according to Table 1, predominantly anthropogenic activities, which include but are not limited to, the gradual degradation of plastic materials and specific farming practices prevalent in these areas. In conclusion, the pervasive presence of microplastics across different land use types not only underscores the extensive environmental footprint of these particles but also calls for urgent and comprehensive strategies to mitigate their impact. The data gathered provides a compelling directive for future research and immediate intervention aimed at addressing this burgeoning environmental challenge.

Initiatives dedicated to uncovering the pathways through which microplastics infiltrate the soil are presently not as developed as those striving to gauge the prevalence of such contamination incidents. A significant portion of existing studies predominantly narrows their focus to identifying precise sources of pollution within isolated land use scenarios, with agriculture being the primary context under scrutiny. Such studies seldom venture into analyses conducted on a larger scale or explore different environmental settings. Although the information derived from Table 1 offers valuable insights regarding the pervasive existence of microplastics within terrestrial ecosystems, there has been a conspicuous absence of scholarly inquiries into this issue set against the backdrop of diverse or alternative environments. This conspicuous research void suggests an opportunity—and a need—for more ambitious scholarly endeavors that undertake assessments at the regional level, embracing a multitude of land use scenarios in the process. The current body of research is somewhat myopic, lacking in studies that take a holistic view of the issue by examining it across different land use paradigms. Consequently, the true scope and magnitude of the problem remain only partially understood and inadequately documented. Our work represents a preliminary attempt to bridge this significant knowledge chasm. Our work aims to expand the current understanding of microplastic pollution in soil by exploring its presence and impact across a diverse range of environmental settings, not just limited to agricultural lands. This broader approach addresses a notable gap in existing research, which often focuses on isolated land use scenarios. By integrating data from various land uses as presented in Table 1, our study will provide a more comprehensive and regional perspective on microplastic contamination. This will contribute to a more holistic understanding of the issue, shedding light on the scale and complexity of microplastic pollution in different terrestrial ecosystems, a crucial step towards developing effective environmental management strategies.

To fully grasp the extent of the microplastics issue, comprehensive research yielding crucial monitoring data on soil microplastics across diverse land-use types is indispensable. Such research should delve into the types of polymers involved, offering critical insights into the sources and nature of this pollution. This expansive approach is crucial for a nuanced understanding, allowing us to tailor effective mitigation strategies to the specific challenges posed by microplastic pollution in various environmental settings. Moreover, understanding the distribution and impact of microplastics in soil is not only essential for environmental health but also has significant implications for various aspects, such as agricultural productivity and food safety. By bridging these gaps, our research will not only contribute to environmental conservation but also to safeguarding public health and ensuring sustainable practices.

3. Research Methodology

In this section, we discuss the locations from which samples were retrieved, providing a detailed overview of the research methodology employed for this study. Moreover, the approach used for analyzing the obtained results is also explained. Each of these components is illustrated and clarified in Figure 2 for a better understanding.

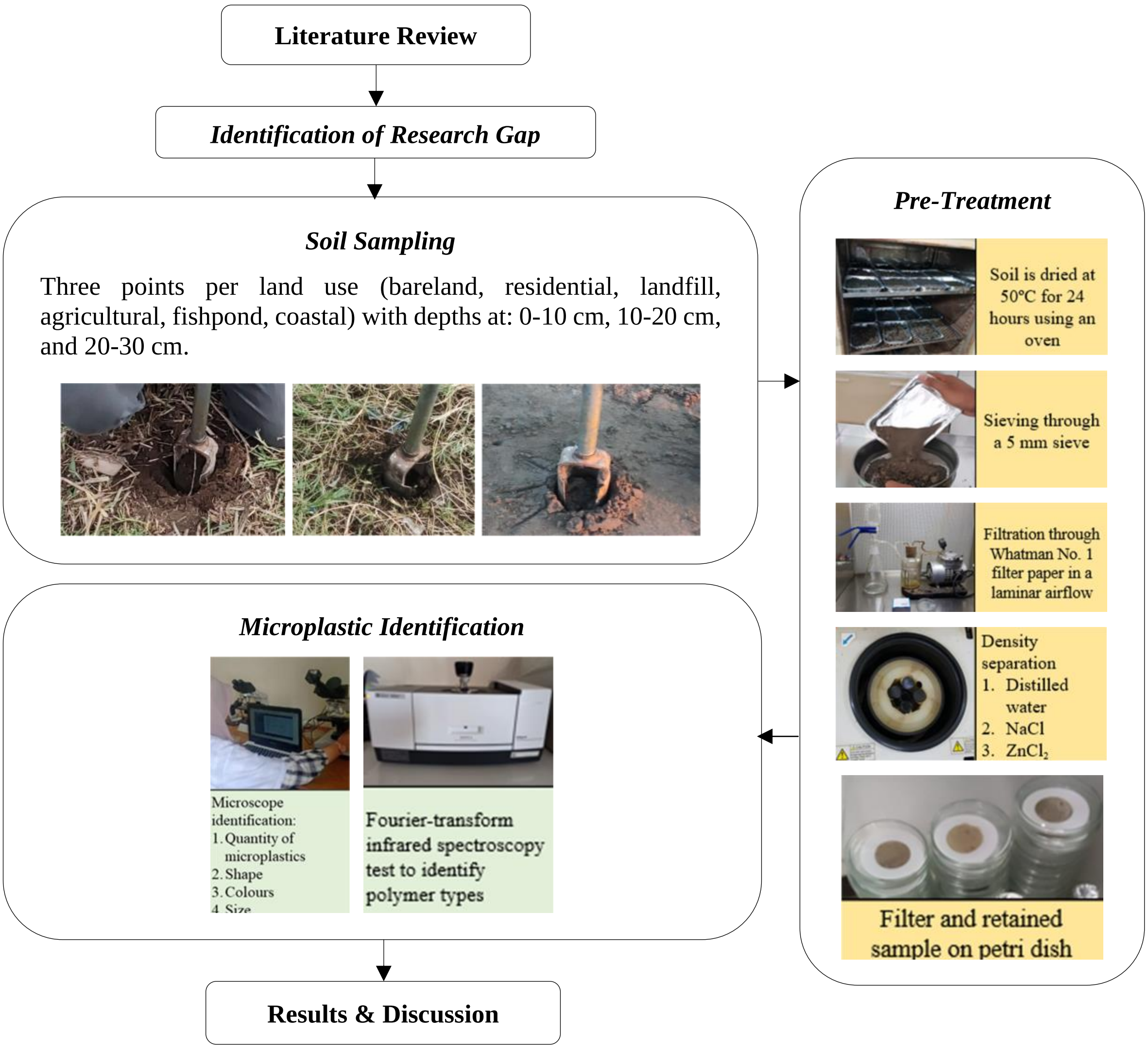


Figure 2. Research Flowchart

3.1. Location

The study took place in Makassar city, Indonesia, home to 1,432,189 individuals as of 2022, experiencing a population growth rate of 0.6% [84]. Arifin et al. [85] estimated that the city encompasses 9392.5 hectares of built-up areas, regions densely populated with houses and other structures, and 7682.4 hectares of unbuilt areas. Soil samples were collected in the dry months of May and June 2023, times characterized by negligible wet atmospheric deposition, with more weather details for these months depicted in Figure 3. Research sites were chosen and categorized based on various land use types within Makassar City, including residential, agricultural, bare land, fishpond/aquaculture, coastal, and landfill areas. For each type of land use, three specific sampling points were selected, as illustrated in the aerial map provided in Figure 4.

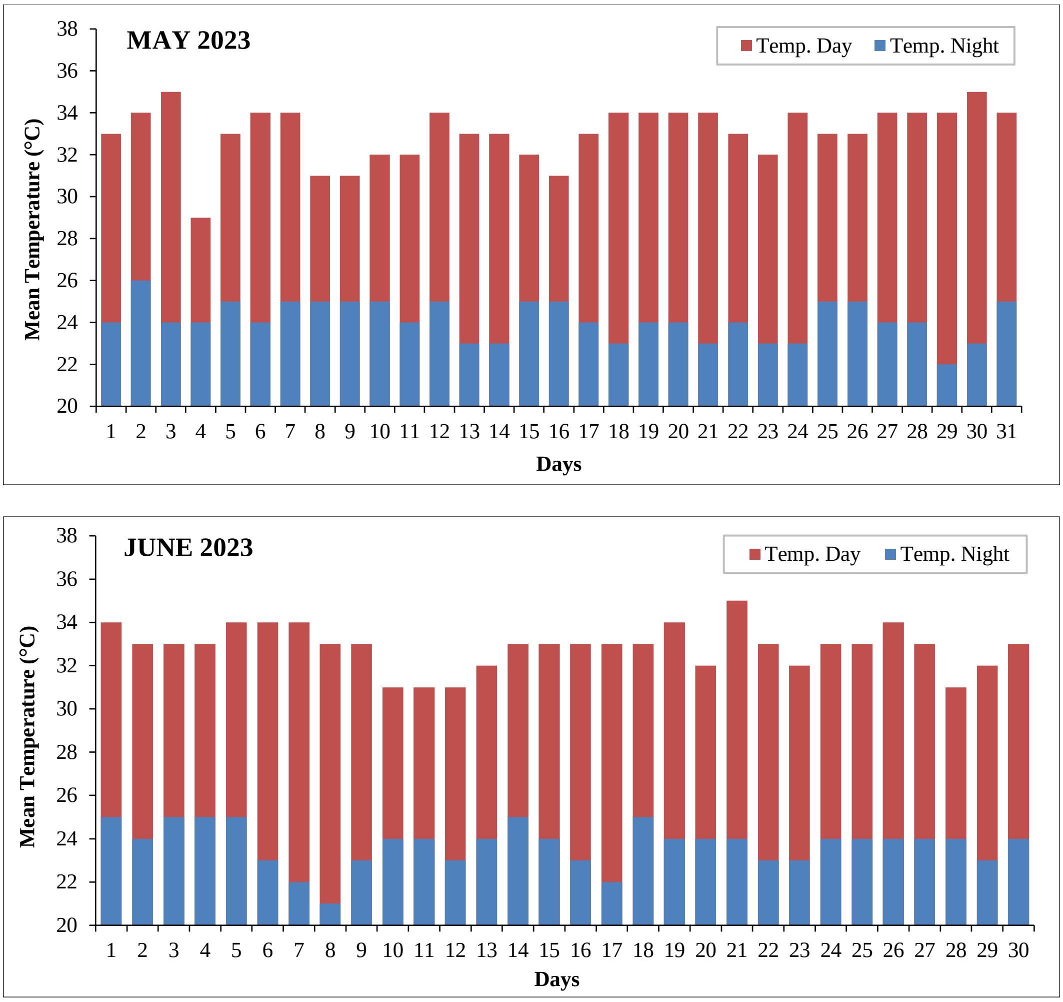


Figure 3. Makassar Weather in May and June 2023 (Samples were collected on May 25, 2023, and June 4, 2023)

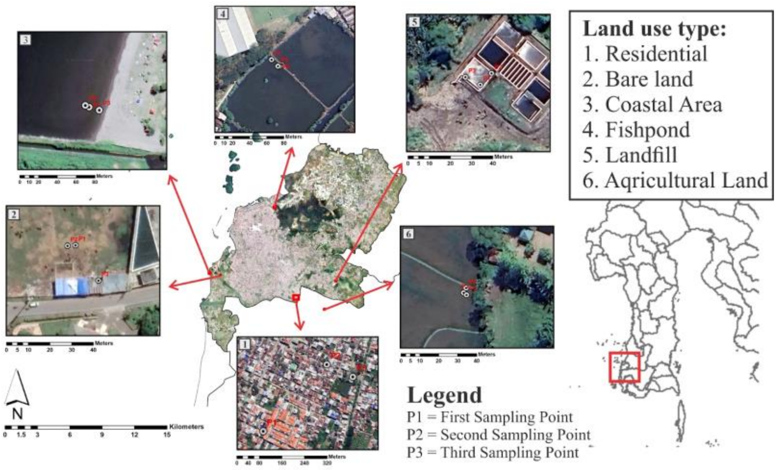


Figure 4. Aerial Map with Sampling Points

3.2. Sample Collection

A total of 54 soil samples were collected from six distinct types of land use, utilizing a borehole apparatus measuring 9.71 cm in length and 8.46 cm in width. For each land use type, soil was extracted from three separate points, with samples taken at three varied depths of topsoil: 0–10 cm, 10–20 cm, and 20–30 cm, in order to see the transport of microplastics in different depths following previous studies [86, 87]. The consideration of stratified soil was also chosen due to the higher levels of activity of soil organisms in those depths, and it is noteworthy that the average depths of rooting and ploughing activities do not surpass 30 cm [88, 89]. Every sample was then carefully placed in aluminium foil, securely stored in a labeled box, and transported to the laboratory for analysis. To minimize the risk of contamination, the sampling process employed little to no plastic materials, tools, or apparatus.

3.3. Pre-Treatment Procedure

Soil samples were initially collected, placed in laboratory storage, and subsequently oven-dried at a temperature of 50°C for a duration of 24 hours, a process aimed at moisture elimination [90, 91]. The application of low temperature during this drying phase is crucial, as it ensures that the concentration and characteristics of the microplastics within the samples remain unaltered [91]. Following the drying process, the samples were then sifted through a 5 mm stainless-steel sieve, a step implemented to isolate microplastics of specific sizes by removing any particles exceeding the 5 mm threshold.

The extraction process of microplastics from the soil samples was executed through a density-based separation method. This method involved the addition of salt to increase the density of the particles, which in turn facilitated the flotation of the lighter plastic materials. Detailed extraction steps were modeled after previous studies conducted by Corradini et al. [66] and Yang et al. [21]. In a summarized format, the process entailed placing 5 g of soil and 20 ml of water (with a density of 1.00 g cm^{-3}) into a glass centrifuge tube, which was then centrifuged at 2000 rpm for 15 minutes. The resulting supernatant was carefully filtered using Whatman No.1 filter paper and a vacuum pump. In the following steps, the tube with the remaining sediment was filled with 20 ml of Sodium Chloride (NaCl 5 M, with a density of 1.20 g cm^{-3}), serving as the chosen salt for the density separation process [92]. The sample was then centrifuged again for 2 minutes at 6,000 rpm, with the supernatant undergoing a second round of filtration. This process was repeated a third time using 20 ml of Zinc Chloride ($ZnCl_2$ 5 M, $\rho = 1.55$ g cm^{-3}) and the sediment was stirred at 6,000 rpm for 2 minutes before a final round of filtration through the same filter paper.

The decision regarding the duration and speed of the second and third centrifugations was initially based on previous research by Corradini et al. [66], which recommended a rotation speed of 21,000 rpm. However, during the process, some tubes fractured at 7000 rpm while increasing the rotation speed. To navigate this limitation, the rotation speed was adjusted to 6000 rpm while simultaneously increasing the duration of the centrifugation process.

To mitigate the risk of external contamination, the filtration process was conducted within a laminar airflow, as suggested by Wesch et al. [93]. Post-extraction, the filters with the samples were securely stored in Petri dishes, ready for subsequent optical examinations.

3.4. Microplastics Identification

Samples in Petri dishes were visually identified using a Sinher binocular digital microscope, adhering to the guidelines set forth by the Marine and Environmental Research Institute [94] and Norén [95] for observing and quantifying microplastic properties. Microplastics are typically quantified as the number of particles per gram of dry soil. These particles were categorized based on morphological characteristics, including various forms like fibers, fragments, films, and pellets. The particles were also classified by color. Image-J software was utilized to measure the size of the microplastics.

For additional identification of potential microplastics, Fourier-transform infrared (FTIR) spectroscopy was employed due to its being a straightforward, reliable, and non-invasive technique with the ability to produce unique band patterns in the infrared spectra for various plastics [96]. The absorption and measurement of radiation—whether in reflection or transmission mode—are influenced by the chemical composition of the microplastics, and this occurs when they are exposed to an infrared sample (with a wave number range of 500–4000 cm^{-1}) [92, 97]. In this study, 108 particles were selected for FTIR analysis using Shimadzu equipment, with the goal of identifying the polymer type of each particle. Each selected particle represents different land uses.

3.5. Data Analysis

The application of descriptive analysis was utilised to evaluate the microplastics, whereby the data was organised based on concentration, type, colour, and size. The statistical software R was employed to perform data analyses, including the application of the Shapiro-Wilk normality test [98] and the T-test, to examine differences in microplastic concentrations across different land uses [99].

3.6. Quality Control and Detection Limit

To mitigate the risk of plastic contamination from external sources during the sampling procedure, sample preparation, and subsequent microplastics analysis, all equipment was rinsed and sterilized before use. Additionally, various non-plastic materials were employed, including aluminum foil, glass beakers, glass centrifuge tubes, and glass Petri dishes. Furthermore, it is important to note that the methodologies used to quantify and identify microplastic polymer types at a microscopic level may have limitations in terms of particle size. In this particular experiment, the minimum size observed was found to be 20 μm. Therefore, it is conceivable that microplastic particles of smaller sizes may have evaded detection.

4. Results

4.1. Microplastics Abundance across Varying Land Uses

Six distinct land uses were examined in this study, with each having varied concentrations of microplastics at different soil depths (as seen in Figure 5). These land uses include bareland, residential areas, landfills, agricultural land, fishponds, and coastal areas. In comparing the microplastics concentrations across these land uses, the landfill area exhibited the highest concentration at the 0-10 cm depth with 23.4 particles per gram. This concentration decreases slightly at deeper levels (20.1 particles per gram at both 10-20 cm and 20-30 cm depths). In contrast, residential areas displayed consistent microplastic concentrations across all depths, with the highest concentration observed at the 20-30 cm depth (21.8 particles per gram). Bareland and agricultural lands also showed similar consistency in microplastics concentrations, albeit with slight variations at different depths. Fishponds showed a reduction in concentration from 19.4 particles per gram at 0-10 cm to 18.9 at 10-20 cm, but then an increase at the 20-30 cm depth with 21.9 particles per gram. Coastal areas had the lowest concentrations at all depths, with an average of 17.1 particles per gram.

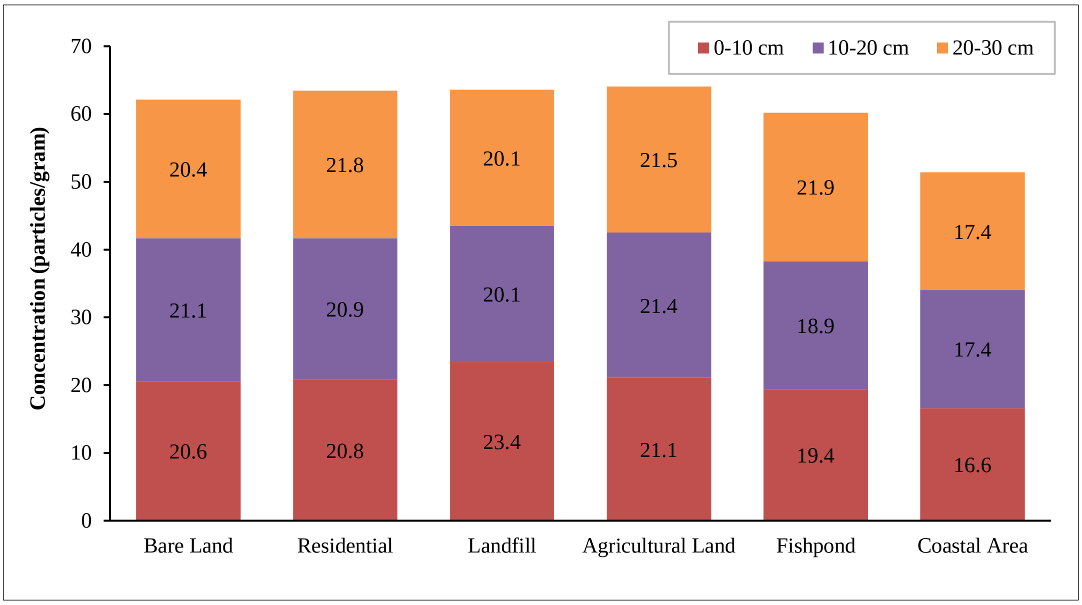


Figure 5. Microplastics Concentration Variations Across Different Land Uses

The observed distribution of microplastics at various soil depths revealed an unexpected pattern. While there is not a definitive trend documented in past studies regarding the prevalence of microplastics with depth, higher concentrations are generally anticipated at surface levels. This expectation is based on the presumption that surface levels are more exposed to microplastic sources and subject to sedimentation processes that trap these particles. However, the data from this study deviate from these expected patterns. Notably, the highest concentrations of microplastics in residential and fishpond areas were not discovered at the surface, but rather at depths of 20-30 cm. This irregular distribution suggests that other influential factors are at play, affecting the movement and deposition of microplastics within the soil strata. Such factors may include the texture and permeability of soil, as well as disturbances caused by human or animal activities.

4.2. Characteristics of Microplastics

The microplastics identified in this research were differentiated based on their shape, color, and size. These features are essential in understanding the complex nature of microplastic particles. Each attribute provides unique insights into the sources, dispersion, and potential environmental impacts of microplastics across various land uses. The findings concerning the shapes of microplastics across six distinct environments in Makassar City are presented in Figures 6 and 7.

Figure 6 presents the results of microplastic identification, highlighting four distinct shapes discovered in soil samples: fragment, film, fiber, and pellets (as further depicted in Figure 7). In bareland, agricultural land, and fishponds, fragments were the most prevalent, constituting over 60% of the identified microplastics. On the other hand, residential areas, landfills, and coastal zones predominantly contained films as the main type of microplastics. Fibers were scarcely observed across all six land uses, and pellets were the least frequent, accounting for 1% or even less.

Further details on the distribution of microplastic shapes across different soil depths can be found in the supplementary materials (Table S1). The prevalence of specific shapes varies with depth. For instance, the proportion of fragments in bare land, landfills, and fishponds diminishes as depth increases. In contrast, residential and agricultural lands show an uptick in fragment percentages with increasing depth. However, in coastal areas, the fragment distribution is inconsistent, with fluctuations observed across the 0-10 cm, 10-20 cm, and 20-30 cm depth ranges.

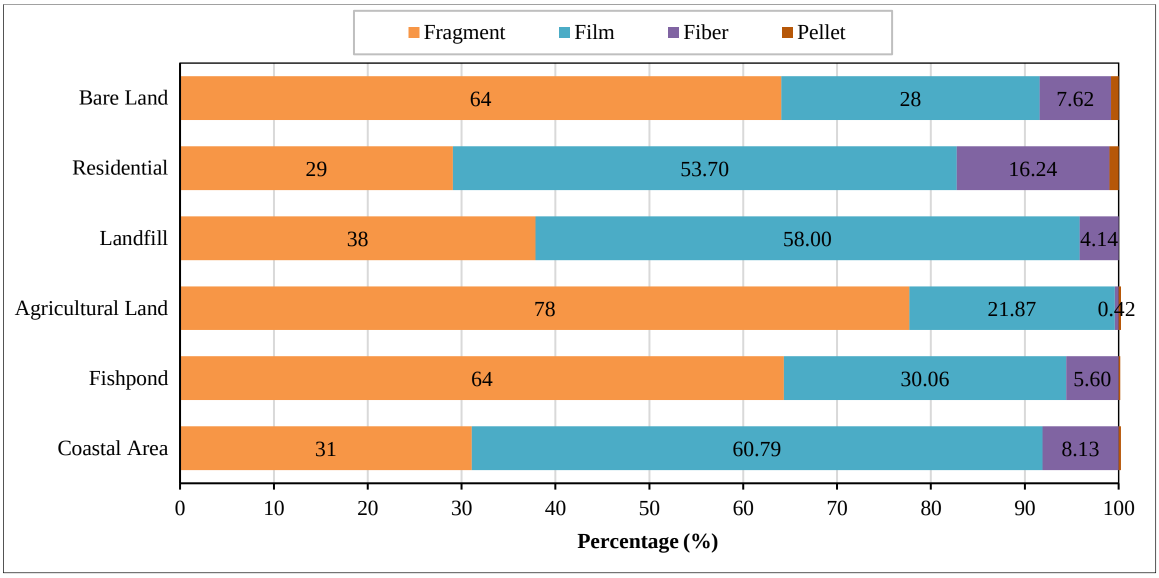


Figure 6. Percentage Distribution of Microplastic Shapes Across Different Land Uses

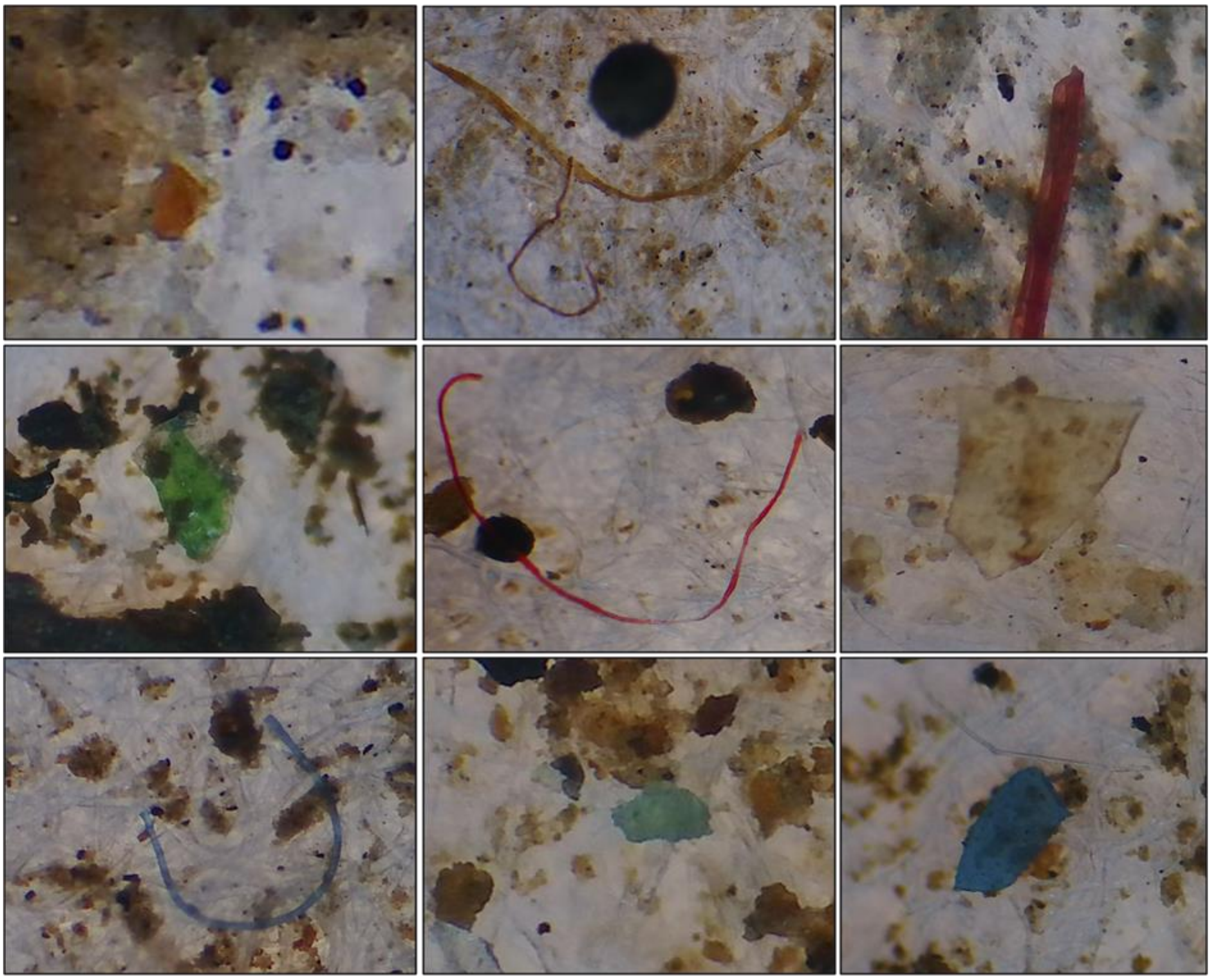


Figure 7. Visual Identification of Microplastic Shapes Using a Microscope

As depicted in Figure 7, microplastics come in a range of colors. The study has revealed intriguing patterns in the distribution of microplastics based on their color across various land uses (as elucidated in Figure 8). Agricultural lands predominantly contain Orange-colored microplastics, making up 36.9% of the samples, closely followed by Yellow at

25.58%, Transparent at 22.49%, and Blue at 14.67%. In contrast, the Coastal Area sees an overwhelming 60.78% of Transparent microplastics, the highest among all land uses. It is also noteworthy that Fishponds and Barelands have a similar distribution with Orange microplastics at 37.6% and 25.93%, respectively, and Transparent ones at 18.54% and 26.21%, respectively.

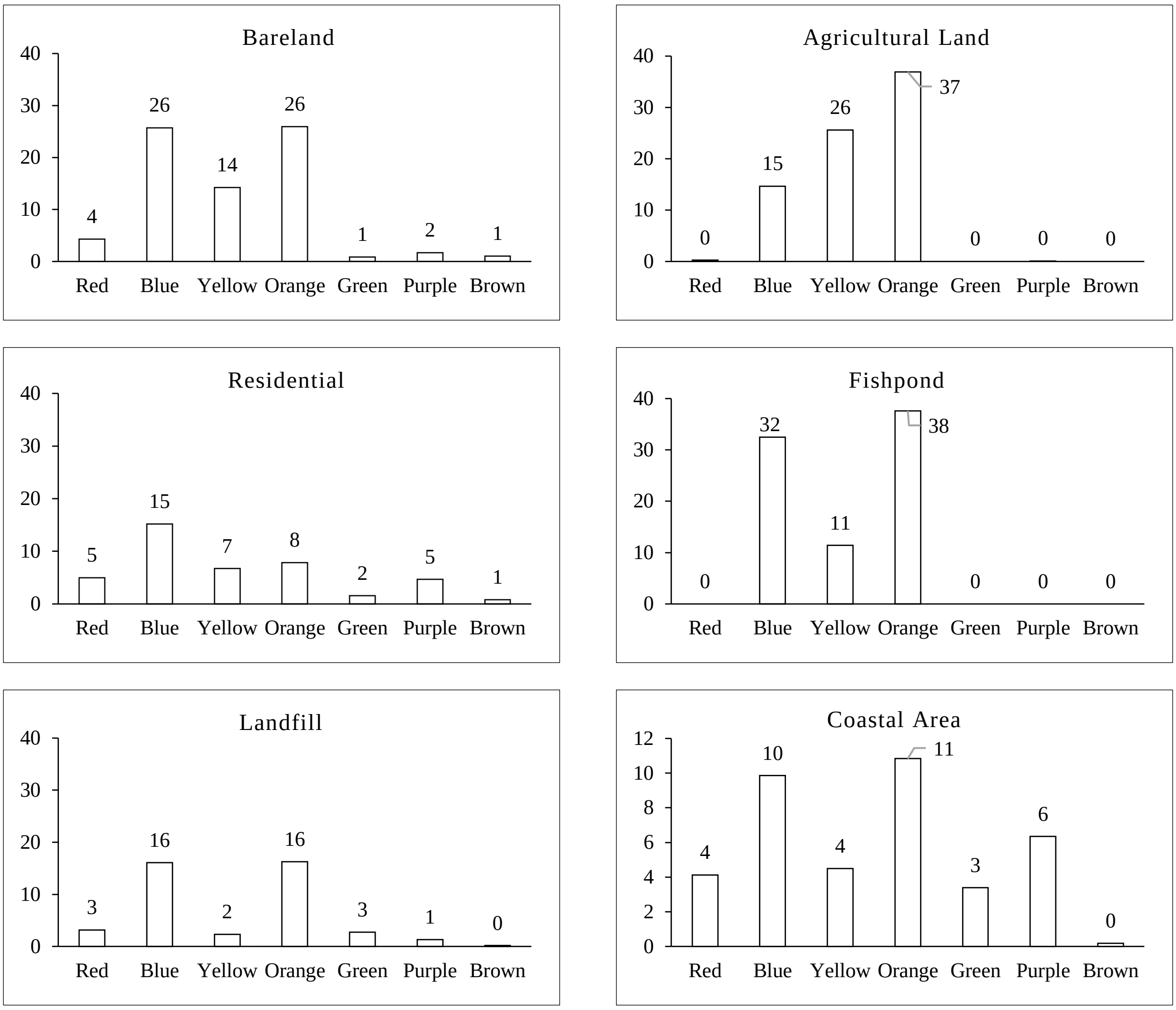


Figure 8. Percentage Distribution of Microplastic Colors Across Different Land Uses

When comparing these results against the land uses, some distinct patterns emerge. For instance, Transparent microplastics dominate in both Landfill and Residential areas, with 57.99% and 58.18% respectively. This could potentially indicate common sources or processes in these areas leading to such accumulation. Conversely, agricultural lands and fishponds have the least Transparent microplastics, hinting at different microplastic sources or the influence of particular activities in those areas. One unusual pattern that stands out is the near absence of Green microplastics in bareland, making up just 0.88%, a stark contrast to other regions. Overall, these findings emphasize the intricate relationship between land use and microplastic distribution. The marked variations in microplastic colors across different land uses suggest different sources, deposition processes, or both.

The distribution of microplastics by color across varying depths for each land use is detailed in Table 2, available in the supplementary materials. The relationship between color and soil depth does not present a consistent pattern. Some colors exhibit fluctuating percentages across the 0-30 cm range, while others, like blue in agricultural land, display a significant reduction from 50.87% to just 3.81% with increasing depth. In contrast, certain colors, such as red in bare land, amplify in prevalence with depth, peaking at 20-30 cm (compared to 7.59% at 0-10 cm). Notably, some colors are specific to particular depths, like the brown microplastics in landfill areas found exclusively at the 20-30 cm depth. In addition, Table 2 provides insights into the size distribution of microplastics across soil depths and the shape of microplastics for each land use.

Table 2. Microplastic Size and Shape Distribution Across Soil Depths for Each Land Use

Depth	Type	Min (μm)	Max (μm)	Size Interval (μm)
Bareland				
0-10 cm	fiber	162	2295	162-2295
	film	46	377	46-377
	fragment	36	306	36-306
	pellet	31	126	31-126
10-20 cm	fiber	128	4453	128-4453
	film	44	471	44-471
	fragment	41	219	41-219
	pellet	29	71	29-71
20-30 cm	fiber	77	1864	77-1864
	film	50	332	50-332
	fragment	39	294	39-294
	pellet	34	144	34-144
Residential				
0-10 cm	fiber	60	2603	60-2603
	film	42	399	42-399
	fragment	34	404	34-404
	pellet	29	70	29-70
10-20 cm	fiber	70	3130	70-3130
	film	46	2765	46-2765
	fragment	43	2316	43-2316
	pellet	54	63	54-63
20-30 cm	fiber	252	3163	252-3163
	film	40	399	40-399
	fragment	48	307	48-307
	pellet	48	62	48-62
Landfill				
0-10 cm	fiber	350	3135	350-3135
	film	41	1207	41-1207
	fragment	37	437	37-437
	pellet	0	0	0-0
10-20 cm	fiber	259	3478	259-3478
	film	33	827	33-827
	fragment	41	666	41-666
	pellet	0	0	0-0
20-30 cm	fiber	419	2562	419-2562
	film	42	499	42-499
	fragment	36	445	36-445
	pellet	0	0	0-0
Agricultural Land				
0-10 cm	fiber	59	862	59-862
	film	51	345	51-345
	fragment	45	305	45-305
	pellet	47	110	47-110
10-20 cm	fiber	148	148	148-148
	film	49	326	49-326
	fragment	37	545	37-545
	pellet	65	65	65-65

20-30 cm	fiber	0	0	0-0
	film	51	322	51-322
	fragment	38	288	38-288
	pellet	0	0	0-0
Fishpond				
0-10 cm	fiber	397	1449	397-1449
	film	51	1254	51-1254
	fragment	55	404	55-404
	pellet	54	56	54-56
10-20 cm	fiber	343	2411	343-2411
	film	61	374	61-374
	fragment	44	307	44-307
	pellet	0	0	0-0
20-30 cm	fiber	151	3163	151-3163
	film	41	625	41-625
	fragment	38	3163	38-3163
	pellet	0	0	0-0
Coastal Area				
0-10 cm	fiber	289	3478	289-3478
	film	33	697	33-697
	fragmen	36	377	36-377
	pelet	50	50	50-50
10-20 cm	fiber	350	3478	350-3478
	film	33	1207	33-1207
	fragmen	42	378	42-378
	pelet	0	0	0-0
20-30 cm	fiber	314	3135	314-3135
	film	33	851	33-851
	fragmen	29	404	29-404
	pelet	0	0	0-0

From the data on microplastic size identification across the six land uses - Bareland, Residential, Landfill, Agricultural Land, Fishpond, and Coastal area - the respective size ranges were determined as 29–4453 µm, 29–3163 µm, 33–3478 µm, 36–862 µm, 38–3263 µm, and 29–3478 µm. These ranges underscore the variability in microplastic sizes across different terrains. Notably, the Agricultural Land exhibits a relatively narrow size spectrum for its microplastics. An intriguing observation across all land uses is that the smallest microplastic sizes were typically found at depths of 20–30 cm, suggesting soil depth could influence the diminution of microplastic size.

The bulk of microplastics identified in this study predominantly fall within the size bracket of less than 100–300 µm, as elaborated in the supplementary materials. On bare land, most microplastics measure less than 100 µm. However, in Residential, Landfill, Agricultural Land, Fishpond, and Coastal areas, the majority of microplastics span a size range of 100–300 µm.

4.3. Identification of Polymers in Microplastic Samples Across Diverse Land Uses via FTIR Analysis

distinct microplastic polymer distribution, shedding light on the variety and dominance of microplastic types present (refer to Figures 9 and 10). Out of 108 samples, with 18 particles tested per land use via FTIR, two particles were identified as non-plastic: a soluble starch in Agricultural Land and a Microfibrillated Cellulose in ponds. These two particles were excluded from data analysis.

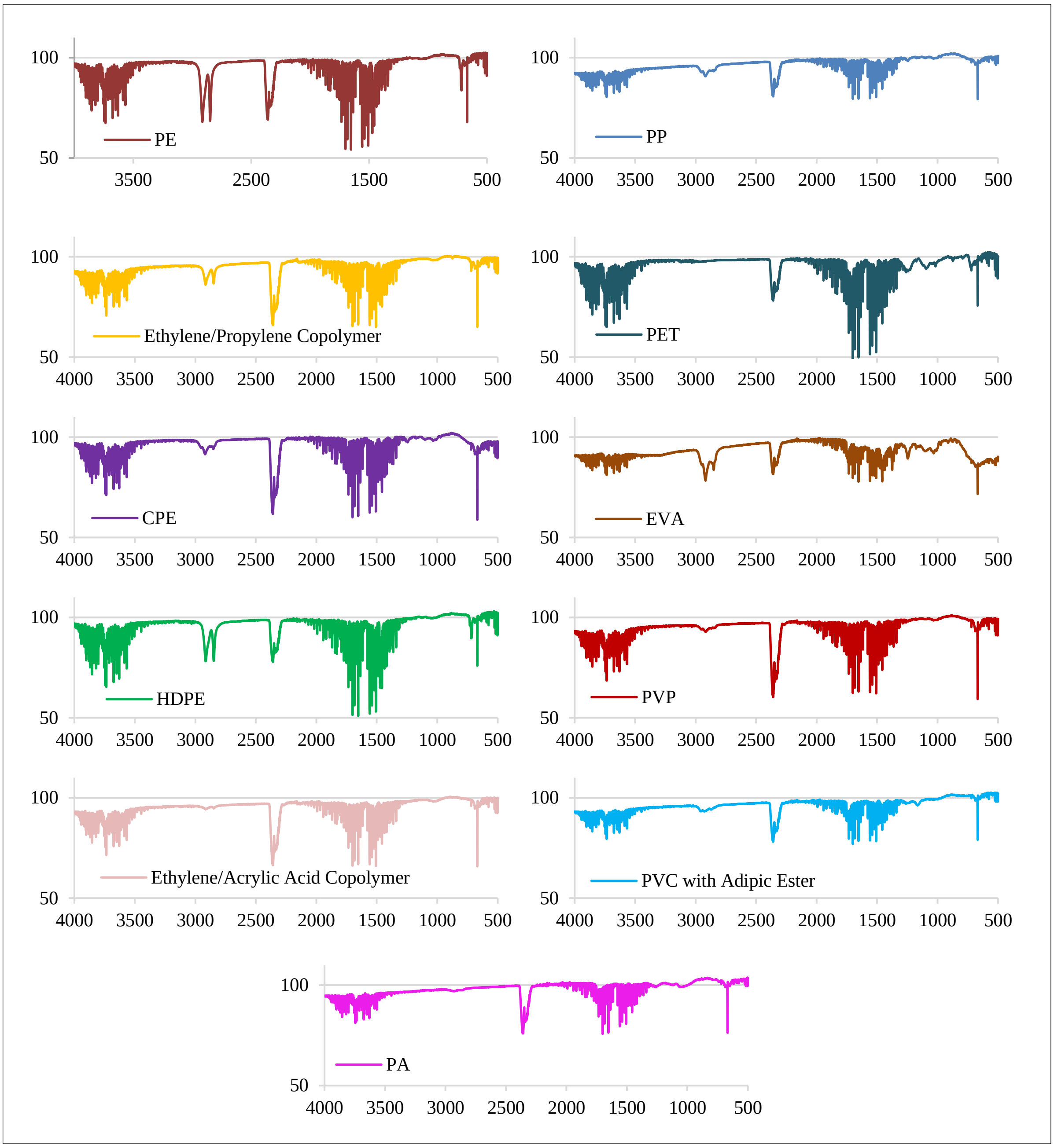
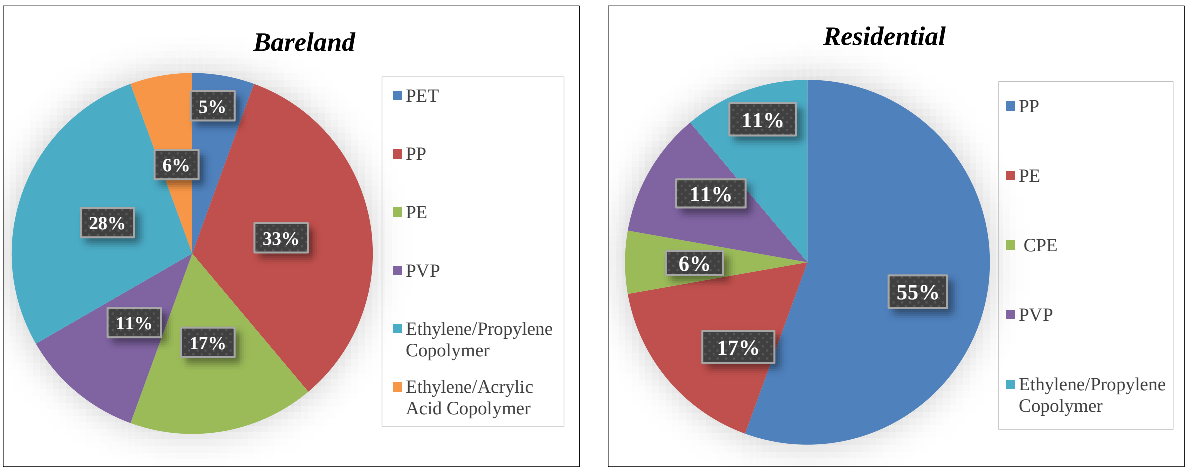


Figure 9. FTIR Spectral Analysis of Microplastics



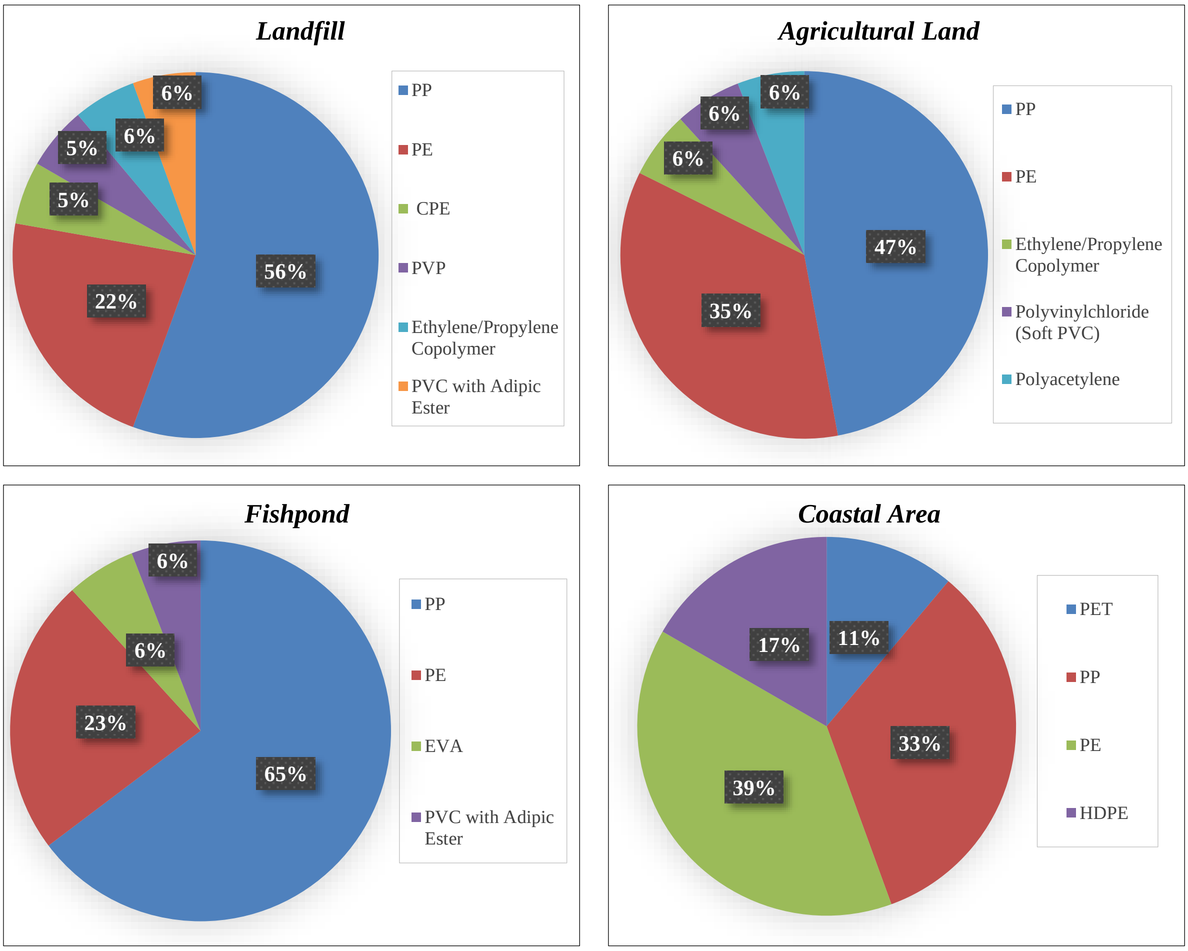


Figure 10. Distribution of Identified Polymers in Microplastic Samples from Various Land Uses

Through careful analysis of the results, a discernible pattern in the distribution of microplastic polymers emerges across the varied land uses. Polypropylene (PP) and Polyethylene (PE) are the two most frequently identified polymers in all land use types, signifying their widespread use and persistence in different environments. For instance, PP constitutes a significant percentage of the microplastics found, ranging from 33% in barelands to 65% in fishponds. Similarly, PE is present in noteworthy proportions, from 17% in barelands, residential areas, and landfills to 39% in coastal areas. Other recurrent polymers identified include Ethylene/Propylene Copolymer, Polyvinylpyrrolidone (PVP), and Chlorinated Polyethylene (CPE), albeit in varying and generally lower percentages.

Upon closer examination of the data, certain similarities and differences become evident in the polymer distribution among different land uses. While PP and PE are prevalent in all environments, their concentrations vary considerably, potentially reflecting the dominant types of plastic waste in each area. Barelands, for example, exhibit a diverse range of polymers, with Ethylene/Propylene Copolymer also featuring prominently at 28%. In contrast, fishponds predominantly contain PP (65%) and PE (23%), with minimal variation in other polymer types. Furthermore, certain polymers are exclusive to specific land uses; for instance, Polyvinyl Chloride with Adipic Ester is found only in landfills and fishponds, while Polyacetylene is unique to agricultural lands. These findings highlight the complex interplay between land use and microplastic pollution, with each environment reflecting a distinct profile of polymer types and concentrations. The observed patterns may be attributed to various factors, including the type of plastic products commonly used or disposed of in each area, the presence of waste management facilities, and the mechanisms of plastic degradation and transport unique to each land use type. Understanding these patterns is crucial for developing targeted interventions to mitigate microplastic pollution in different environments.

4.4. Statistical Analysis and Compatibility Testing of Microplastic Concentrations Across Various Land Uses

The normality test results for six different land uses reveal that five out of the six categories exhibit a normal distribution at a predetermined significance level ($\alpha = 0.05$). The land use associated with fishponds yields a p-value of 0.001117, which falls below the preset level of significance, thereby deviating from normal distribution. Consequently, in light of the derived data, the decision was taken to perform compatibility tests between various land uses utilizing two separate methodologies.

For data on microplastic concentrations demonstrating a normal distribution, statistical analysis was conducted through the application of the t-test method. It is imperative to acknowledge that the foundational assumption underpinning this test is the adherence of the examined data to a normal distribution. In cases involving fishpond land use, where the data diverges from normal distribution, all subsequent statistical tests were examined using the Mann-Whitney test method.

Table 3 elucidates that certain land uses under investigation do not exhibit significant differences in microplastic concentrations, as evidenced by the resultant p-values exceeding 0.05. However, this was not the case for coastal areas, which, when compared to other types of land use, produced p-values less than 0.05. This discrepancy was particularly evident when coastal areas were analyzed against Bare Land (p-value = 0.0188), Residential (p-value = 0.0184), Landfill (p-value = 0.0088), and Agricultural Land (p-value = 0.0043) through the t-test method. In essence, Table 3 substantiates that while microplastic concentrations are fairly consistent across various land uses, coastal areas represent a notable exception.

Table 3. Statistical Analysis of Microplastic Concentrations across Diverse Land Uses

Model	Land Use Type	Normality Test (p-value)	Vs	Statistical analysis	
			Land use type	T Test	Mann-Whitney Test
				(p-value)	(p-value)
1	Bareland	0.1191	Residential	0.7044	-
2			Landfill	0.6208	-
3			Agricultural Land	0.4225	-
4			Fishpond	-	0.7908
5			Coastal Area	0.0188	-
6	Residential	0.5939	Landfill	0.974	-
7			Agricultural Land	0.8591	-
8			Fishpond	-	0.4795
9			Coastal Area	0.0184	-
10	Landfill	0.05463	Agricultural Land	0.8565	-
11			Fishpond	-	0.377
12			Coastal Area	0.0088	-
13	Agricultural Land	0.4527	Fishpond	-	0.6582
14			Coastal Area	0.0043	-
15	Fishpond	0.001117	Coastal Area	-	0.1329
16	Coastal Area	0.9465	-	-	-

5. Discussions

5.1. Microplastics Prevalence and Characterization across Diverse Land Use

In this study conducted at a regional scale, compelling evidence was discovered pertaining to the presence and abundance of soil microplastics across six distinct land-use categories: bareland, residential areas, landfills, agricultural land, fishponds, and coastal areas. The microplastic concentrations ranged between 16.6 to 21.9 particles/gram across all land uses, surpassing numbers reported in previous studies [71, 74-79, 80-83]. The elevated concentration of microplastics in Makassar city can be ascribed to its inefficient waste management system, societal behaviors, and the potential for microplastics to migrate across various locations and environments.

In this study, fragments and films predominantly represented the microplastics in various land-use types. This contrasts with Yang et al. [21], who found that fragments and fibers were the most common microplastic shapes; our study identified only a limited presence of fiber microplastics. The prevalent occurrence of fragment and film microplastics can be traced back to larger plastic debris breaking down into microplastic particles due to processes like mechanical wear, UV light exposure, and biodegradation [21, 100].

This research also revealed microplastics of diverse colors. Past observations indicate that disposable plastic items often degrade into clear microplastics, while long-lasting plastic items tend to yield colored microplastics [101]. Given these findings, it is inferred that the majority of microplastics in residential, landfill, and coastal areas likely originate from disposable plastics. In contrast, microplastics in bareland, fishponds, and agricultural land may predominantly arise from the breakdown of more durable plastic products.

Concerning the type of polymer in microplastics, studies have commonly reported PE and PP as the prevalent microplastic polymers in soil environments [79, 102]. Our findings, based on FTIR results, align with these reports. The widespread presence of PE and PP is understandable, considering they rank among the most globally used plastics. They feature prominently in personal care and cosmetics, as well as in plastic bags and packaging [103].

Microplastic distributions were largely consistent across different land-use types, with the exception of coastal areas. The disparity in coastal regions is attributed to the diverse sources of contamination. Coastal areas not only receive microplastics from terrestrial sources but also directly from oceanic ones. As per [76], coastal microplastics might stem from discarded waste, and it is noteworthy that Indonesia ranks second in oceanic plastic waste contributions globally [104]. Asmal et al. [105, 106] emphasized the challenges of plastic waste and broader waste management in the coastal regions bordering the Makassar Strait. Wicaksono et al. [34] found microplastics in both water and sediment samples of the Tallo River, which flows into the Makassar Strait at Bosowa Beach. Díaz-Mendoza et al. [107] proposed that seawater microplastics can traverse laterally, potentially augmenting the microplastic levels on coasts. This study, examining the lower reaches of the Tallo River, similarly identified microplastics in the adjacent coastal soils. Interestingly, despite the microplastic presence, these coastal sampling sites showed no overt plastic debris, setting them apart from residential, agricultural, and pond areas. Water from the Tallo River, laden with microplastics, is influenced by a variety of sources, including laundry effluent, cosmetic granules, and other household waste. This claim is bolstered by the prevalent detection of PE and PP in our samples, the very polymers associated with these sources. These polymers have also been identified in recent coastal studies in Singapore [75] and Taiwan [76].

Landfills and waste disposal sites have traditionally been identified as major hotspots for microplastic accumulation. Interestingly, the concentration of microplastics detected in this study's landfill was somewhat lower than that in fishponds. This can be attributed to the sampling being conducted in the peripheral soil surrounding the landfill — an area with scattered rubbish — rather than its central section. Notably, Makassar city's landfill employs an open dumping system, leading to a towering pile of mixed waste, approximately 20 m high [108]. For detailed visual insights, refer to the supplementary materials provided. Various polymers, including PP, PE, CPE, PVP, Ethylene/Propylene Copolymer, and PVC with adipic ester, were detected in the Makassar landfill. Such findings align with other research on soil microplastics in landfills [72-74], where similar polymers were identified. The presence of these polymers is likely due to the degradation and fragmentation of plastic waste [72-74]. For instance, this study identified PVC with adipic ester in the form of a transparent film. This variant of PVC incorporates biodegradable plasticizer additives derived from adipic acid esters. These additives enhance the PVC's biodegradability, allowing it to break down in natural settings [109]. Consequently, the detected microplastics are likely remnants from microbial activity breaking down the PVC material.

Fishponds, among the various land uses examined, exhibited the highest average microplastic concentration. The dominant type in these areas was an orange-colored fragment associated with the PP polymer. Field observations, detailed in supplementary materials, indicate that these fishponds are in proximity to residential zones. Many floating PP-based trash items—like food containers, bottle caps, and assorted plastic packaging—were spotted in these ponds, suggesting them as potential microplastic sources. Notably, the polymer EVA was identified solely in fishponds. This polymer is widely used in the insulation and sheath layers of cables [110], hoses, tubes, and footwear [111]. Furthermore, as indicated by a study from Hungary [69], microplastics in fishponds could originate from organism uptake. Scheurer and Bigalke [112] also posited that microplastic pollution in floodplain zones might result from the dispersion of microplastics in water or their aeolian transportation.

In the case of agricultural land, microplastic characteristics largely mirror those observed in fishponds: the predominant shape is fragmented, the color is orange, and the associated polymer is PP. Past studies [78-82] suggest that microplastics in agricultural terrains might stem from farming practices such as plastic mulching, sewage sludge applications, nearby roadways, and urban influences.

In residential areas, it is noteworthy that fiber microplastics constitute approximately 16.24% of the total, a figure significantly higher than in other land uses where it is less than 10%. This can likely be attributed to the fact that most fiber particles stem from clothing or textiles, and residential areas naturally experience the highest human activity. The FTIR analysis revealed that the fiber microplastics found in residential areas are primarily composed of PE, a material extensively used in the textile industry [113]. In addition to PE, other polymers identified in this land use—much like in bare land—include PP, Ethylene-propylene copolymer, PVP, and CPE. Ethylene-propylene copolymer, a synthetic rubber, finds its applications in automotive components, building construction, and the cable sector [114]. Conversely, PVP is utilized broadly in food, pharmaceutical, and cosmetics industries [115], while CPE is popular in various applications such as piping, roofing, and a range of automotive and construction materials [116].

Potential microplastic sources in residential areas and bare lands might include road or vehicle emissions, given the proximity of sampling points to streets, as well as construction activities. Additionally, illegal waste practices, such as littering and inadequate waste disposal, can also contribute to the heightened microplastic concentrations [103]. This is especially true for barelands, which often bear the brunt of illegal dumping, including the discarding of single-use plastics. For a more comprehensive visual perspective, please refer to the supplementary materials provided.

Microplastics are generally defined as particles smaller than 5 mm in size. Notably, in this study, the predominant size of microplastics was found to be under 300 µm. This minute size can have significant implications for toxicity [117]. The heightened potential threat of these tiny microplastics to organisms is due to their expansive surface area, enhancing the absorption of harmful compounds. Furthermore, their diminutive size makes them easily ingestible by various species because they are less noticeable [21, 118].

Given that this research represents the inaugural study on soil microplastics across different land uses in Makassar City, Indonesia, there is a pressing need to delve deeper into the specific origins and pathways of microplastics within each land use. This study marks a significant advancement in understanding soil microplastic pollution, revealing higher concentrations of microplastics across various land uses than previously reported. It diverges from prior findings (e.g., Yang et al. [21]) by predominantly identifying fragments and films, rather than fibers, suggesting different sources and degradation processes. The research highlights the distinct microplastic contamination patterns in coastal areas, attributed to combined terrestrial and oceanic sources. Surprisingly, fishponds exhibited higher microplastic levels than landfills, challenging conventional assumptions and pointing to complex pollution sources. The study also confirms the dominance of polymers like PE and PP, aligning with global plastic usage trends. Notably, the significant presence of fiber microplastics in residential areas indicates the impact of human activities, particularly from textiles. The small size of these microplastics raises concerns about their potential toxicity and threat to organisms, underscoring the urgent need for comprehensive studies to explore the origins and pathways of microplastics in different environments.

5.2. Comparative Insights: Distribution and Pathways of Microplastics Across Land Uses and Depths

The findings of the current study on microplastics concentrations across various land uses unveil intriguing comparisons and contrasts with previously documented studies. Landfills in this study showed the highest concentration of microplastics at the surface depth (0-10 cm), aligning with general expectations that microplastics predominantly occur at surface levels due to the continual deposit of waste materials. Nevertheless, the observation of elevated concentrations at lower depths, especially in residential and fishpond areas, diverges from conventional anticipation, suggesting the presence of distinctive distribution mechanisms in these environments.

In the current study, the notable presence of plastic waste, observed visually at various soil depths in fishponds, bareland, landfills, and residential areas, underscored the pervasive existence of microplastics (available in supplementary materials). This presence is particularly pronounced in urban and agricultural soils, which are often considered hotspots for microplastic pollution due to their close proximity to human activities. Such activities invariably generate plastic waste externalities, contributing significantly to the microplastic content [119, 120]. This situation reflects the findings of Xu et al. [49] and Helmberger et al. [121], who explored the complex journey of microplastics within the soil environment. Upon entering the soil, microplastics undergo various interactions and transformations, neither remaining static nor inactive. A dynamic interplay exists between abiotic and biotic mechanisms [50-53], with each playing a crucial role in the dispersal and distribution of microplastics. The recorded presence of earthworm activity within the soil of residential, agricultural, and fishpond areas in the present study exemplifies this dynamic interaction. Such biological activities, especially those associated with earthworm burrowing, not only increase soil porosity but also enhance water infiltration rates, thereby actively influencing the movement and distribution of microplastics throughout different soil layers [122].

The distinct granular constitution of the soil in these coastal areas, which differs significantly in porosity from the predominantly fine-grained soils found in other land uses, facilitates easier penetration of microplastics. Given these observations, future studies should explore how soil characteristics may influence the rates of microplastic deposition and the pathways they traverse within the soil profile.

In reflecting on these insights, it is imperative to acknowledge that the movement and penetration of microplastics within the soil matrix are multifaceted processes influenced by both abiotic factors and biological activities. The observed variations in microplastic concentrations at different depths across diverse land uses, as evidenced in both the present and past studies, highlight the dynamic interactions within the environment that govern the behavior and distribution of microplastics. Understanding these nuances is crucial for devising effective strategies to mitigate the impact of microplastics on our ecosystems and public health. Hence, future research endeavors should continue to explore and elucidate the myriad factors influencing the pathways and fate of microplastics in various terrestrial environments.

5.3. Potential Impact of Microplastics Pollution

This study uncovers significant potential implications of microplastics across various land uses on the ecosystem. The dominant presence of small-sized microplastics (less than 300 µm) suggests an increased likelihood of accumulating and transferring contaminants, such as organic pollutants, human pathogens, and heavy metals [123]. This can jeopardize the balance of soil microbial populations and biological activities, resulting in ecological disruptions [124-126]. The physical structure of the soil may also be altered due to the integration of these microplastics, potentially compromising land fertility and integrity [127]. Predominantly, the identified microplastics were of PE and PP varieties. Notably, PE has been found to significantly reduce soil pH [128] and influence the soil's carbon and nutrient cycles [129]. In agricultural settings, such plastic particles can adhere to plant root exteriors, potentially hampering plant productivity [130, 131]. The discovery of microplastics in residential areas amplifies health concerns, given the potential for airborne microplastics or their transition into water bodies. Such pathways can lead to human exposure through inhalation, ingestion, or skin absorption, raising alarms about health risks [132]. Moreover, once inhaled, denser particles could reside in the lungs, later entering the circulatory and lymphatic systems [133]. Considering this study pioneers the research on soil microplastics in Makassar City, Indonesia, there is an imperative need for further exploration. Specifically, assessing the nuanced impacts of microplastics across varied land uses is crucial, especially in the context of an expanding population and the anticipated rise in microplastic concentrations in these environments.

5.4. Recommended Mitigation Strategies

The elevated presence of microplastics in soil poses a significant environmental concern that demands immediate and effective intervention. As highlighted earlier, the repercussions of unchecked microplastic contamination can be detrimental, both ecologically and in terms of human health. This research suggests a suite of mitigation strategies tailored to specific land uses, emphasizing proactive prevention of further contamination. Each land use type necessitates a distinct approach for effective mitigation.

For agricultural terrains, bioremediation emerges as a viable solution. This technique leverages microorganisms to degrade plastic residues into benign substances [134]. Not only is this approach effective for farmlands, but coastal areas can also benefit from it to neutralize prevalent contaminants [135]. Additionally, reforesting areas surrounding agricultural land can significantly diminish the influx of microplastics into the soil [136]. Implementing vegetation like reeds and peanuts, known to assimilate byproducts from microplastic degradation [137], can further mitigate the spread and impact of these contaminants.

Coastal contamination is intricately linked to water flows from inland channels, especially rivers [34]. These river flows transport microplastics from diverse sources. To effectively combat the widespread problem of microplastic contamination in coastal regions, a comprehensive strategy is imperative due to the varied routes through which microplastics spread. While curtailing the use of plastic products and ensuring they do not end up in rivers is essential, other critical measures include improved waste management systems that effectively filter out plastics before they reach coastlines or oceans. Additionally, raising public awareness about the detrimental effects of microplastic pollution and enforcing strict regulations on microplastic discharge from industries and manufacturers are vital components of this holistic approach.

6. Conclusion

In our detailed study of the prevalence, distribution, and ecological implications of microplastics in soil environments, particularly within Makassar City, Indonesia, we have elucidated several significant findings. This research underscores the pervasive nature of microplastics across a variety of soil types and land uses, highlighting their widespread presence. The study yielded three primary insights: Firstly, microplastic concentrations were found to range between 16.6 to 21.9 particles per gram across all land uses, with a noted consistency in these levels except for coastal areas. Secondly, our research demonstrated a notable variance in the distribution of microplastics, with distinctions in shape, color, and size observed at varying soil depths. Furthermore, our analysis revealed diverse attributes of microplastics, such as the predominance of fragments and films across different land uses. We identified a spectrum of colors, including blue, green, orange, purple, red, transparent, and yellow, with polyethylene (PE) and polypropylene (PP) emerging as the principal polymers. Most microplastics were also found to be less than 300 µm in size.

Our findings regarding the movement and distribution of microplastics within soil indicate a non-uniform pattern, which could have substantial consequences for soil-dwelling organisms and the broader ecosystem. This underlines the critical need for more comprehensive studies on the ecological impacts of soil microplastic pollution. Nonetheless, our research acknowledges certain limitations, such as the essential requirement for standardized methodologies in the study of microplastics, the complex challenges in analyzing diverse particle sizes and compositions, and the evolving understanding of the chemical and physical properties of microplastics in soil. Therefore, future research endeavors should focus on addressing these challenges and building upon the foundational insights provided by our study. The significance of this research lies in its contribution to the broader understanding of microplastic pollution, offering vital information for the development of effective environmental management and conservation strategies. This is crucial for safeguarding soil health and ensuring the sustainability of ecosystems.

7. Declarations

7.1. Author Contributions

Conceptualization, M.A.W., Z.A.H., R.H., and A.D.D.; methodology, M.A.W., Z.A.H., R.H., and A.D.D.; laboratory administration, Z.A.H., R.H., and A.D.D.; investigation, M.A.W., Z.A.H., R.H., A.D.D., and S.N.; writing—original draft preparation, M.A.W., Z.A.H., and R.H.; writing—review and editing, M.A.W. and Z.A.H.; supervision, M.A.W., Z.A.H., R.H., S.N., K., and L.C.; funding acquisition, M.A.W. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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