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Microplastics: Notes on Recycling, Waste, and Environmental Prevalence

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1. Problem Statement

Microplastics (MPs), industrial byproduct plastic particles less than 5 mm in size [1], have emerged as pervasive environmental pollutants, posing health risks to biological ecosystems through a variety of mechanisms. These mechanisms include uptake pathways in plants, whose contamination affects their physiological processes. While their unapparent size and ubiquitous nature can make microplastics an easy subject to overlook, the long-term potential harm of microplastics on our environment warrants attention.

Currently, approximately 40% of single-use plastics are discarded into land and waterways, whose active processes can further degrade them into micro- and nano-size particles [2]. These microplastics can carry hazardous chemicals that can cause serious health risks such as human cell injury, hormone disruption, and cardiovascular disease. Colloquially known as 'microplastics', these debris are highly permeative and traverse through the environment with ease, eventually impacting plant physiology. Through ingestion, their introduction into the bodies of animals, including humans, has also been known to cause cytotoxicity, unnoticed inflammation responses, hormonal disruptions, and more [3]. The resulting damages have included acute organ disease and general disorder of biochemical constitution.

Thus, it is critical to analyze the mechanisms of soil, water, and air dispersal of microplastics and their corresponding assimilation into plants. By studying these mechanics of plant permeation, it becomes possible to devise strategies to eliminate their detriments to the environment and health.

2. Types of Pollution and Methods of Emission/Access to Environment

Microplastics are primarily categorized into two sections: primary and secondary. Primary microplastics are already in miniature form, meaning they do not undergo the same degradation process that other, larger plastics do [4]. These microplastics have specialized use in cosmetics, drug carriers, and other industrial purposes. Examples of these sources of environmental MP contamination are shown in *Figure 1*. Since they are already in form—round, granular and non-degradable—they can escape sewage treatment processes and make their way into natural habitats by way of polluted water or sludge [5].

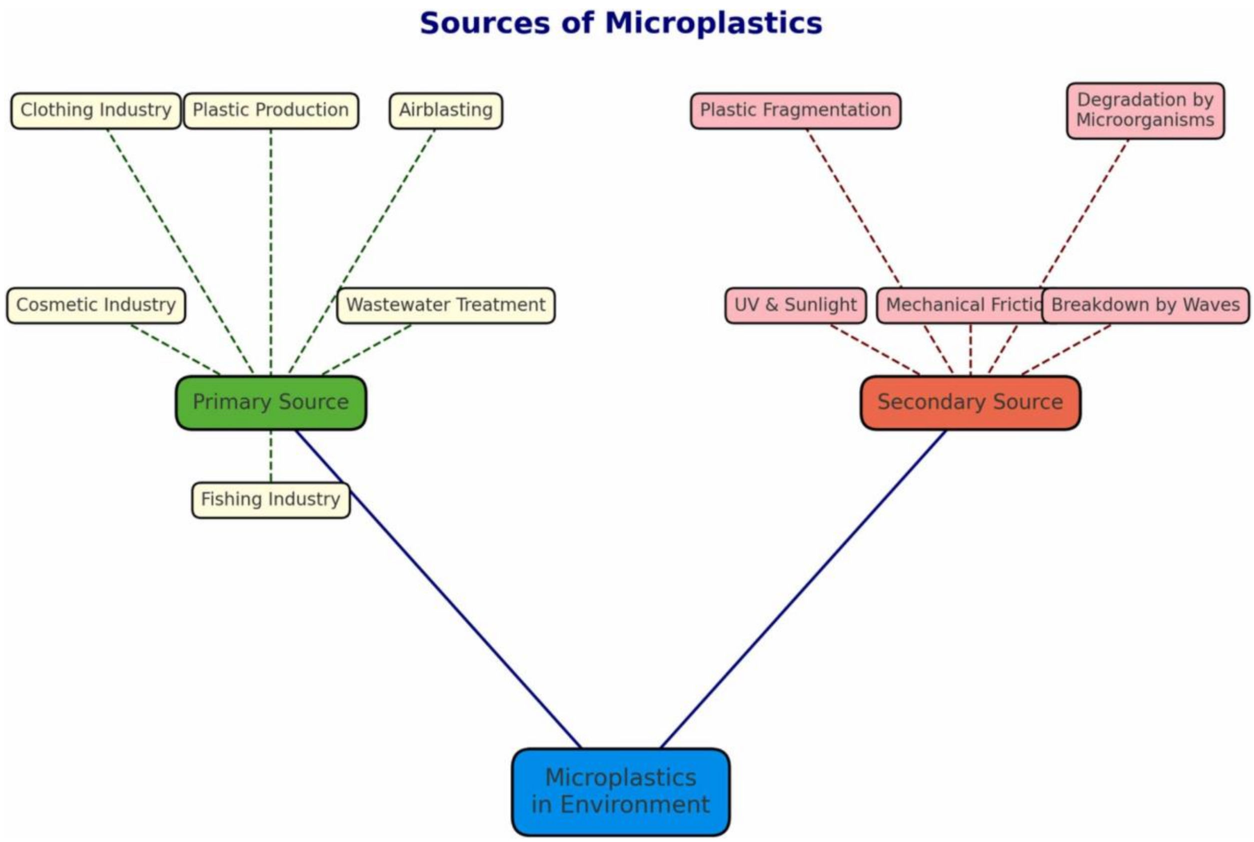

Figure 1: 'Sources of Microplastics', adapted from Hasan et al 2024 [6]

The large majority of microplastics that make their way into the environment are ones that were broken down from larger plastic objects, hence called secondary microplastics [7]. Through environmental wear and tear such as UV light, wind, and mechanical roughness, the larger plastics break down into problematic fibres, chunks, and granular particles of various sizes [8]. These microplastics then migrate to different ecosystems via landfill waste, crop-plastic film, organic fertilizers, contaminated irrigation water, and atmospheric deposition.

3. Mechanisms of MP-Plant Contamination:

3.1 Introduction:

The mechanisms by which microplastics permeate into plant systems focus primarily on two organs and their specific uptake mechanisms: (1) root cells for plant ingestion, and (2) stomata for plant respiration. In each organ, soil, water, and air act as vehicles of MP transport and infiltration.

Root cells are the fundamental components of the plant's root system, responsible for the absorption of water, anchorage to the soil, as well as storage and transport of other intaken nutrients [9]. On the molecular level, root cells have extensions called root hairs that elongate outward into the soil in order to maximize surface area for water absorption [10]. Inside these extensions, high concentrations of solutes such as minerals and sugars can create an osmotic potential and facilitate the movement of water into the cell [11]. Additionally, root cells possess a unique quality called hydrotropism, meaning the cells will tend to elongate towards moist regions of the soil [12]. This phenomenon, especially in drier times, will result in a curvature of root structure towards the damper patches [13]. The branched root system also serves as an anchor for plants, helping to maintain plant and soil stability. Through attaching to bedrock deep in the ground, thick roots act as stabilizing structures and help prevent soil erosion and landslides. This system also allows for the effective transportation of nutrients and other vital minerals to all parts of the plant.

Stomata are pores that plants use for gas exchange and other cellular processes, such as photosynthesis and cellular respiration [14]. Stomata are usually found on leaf surfaces but can sometimes be found on stems as well. The primary purpose of stomata is for gas exchange in photosynthesis and respiration, but it is also responsible for water transpiration, meaning the loss of water in the form of vapor [15]. On the molecular level, the stomata is a pore, enveloped by two guard cells responsible for the opening and closing of the stomata. Guard cells are highly sensitive to environmental cues, especially sunlight, which can regulate stomatal activity [16]. The guard cells mainly regulate through turgor pressure, the pressure that pushes out on cell walls from internal fluid. When the turgor pressure is high, the vacuole expands and opens the stomata, and the same goes in reverse. The vacuole will expand and contract due to fluctuations in potassium and water concentrations, prompted by changes in sunlight that cause changes in proton pumps and effectively then cause changes in ion concentrations [17].

These two organs, root cells and stomata, and their purposes form the basis for understanding how MPs induce toxicity in plants.

3.2 Uptake Mechanisms:

There are various uptake mechanisms for MPs in plants leveraging the various media that they interact with for their routine biological processes. These can include liquid, solid, and gaseous exchange via specialized organs, whose interfacing can inadvertently introduce contaminants into the plant. A general description of the media, used by MPs as transport vehicles towards uptake, is shown in *Figure 2*.

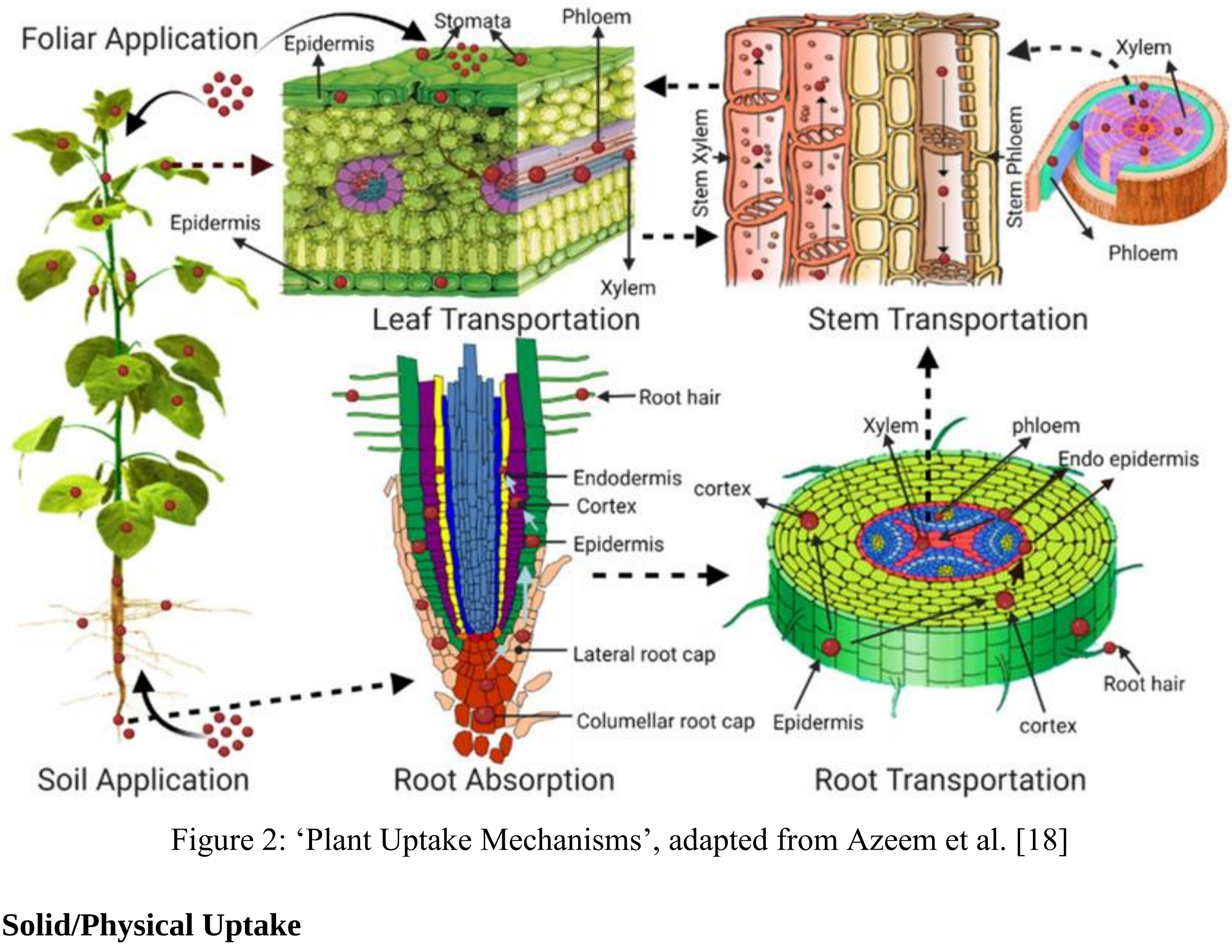

Figure 2: 'Plant Uptake Mechanisms', adapted from Azeem et al. [18]

3.2.1. Solid/Physical Uptake

(i.) MP-Plant Interfacing:

One of the primary methods of uptake in plants is through physical or solid contact with the MPs. Within this category of uptake, the main area of uptake is the roots of a plant. Generally, uptake in this area involves a multi-step process, including adhesion, internalization, and transport. Adhesion in regards to MPs uptake means that MPs in the soil matrix can adhere to root surfaces due to their small size and electrostatic properties. Next, internalization involves the biological process of endocytosis, where the cell membrane will engulf surface particles and ingest it into the cell [19]. Once in the cell, different mechanisms of transport, primarily through the vascular system, will allow these intaken MPs to travel around all parts of the plant [20]. This process can be defined as passive uptake, as MPs can come into direct contact with roots then the root hairs can facilitate transport into the root cells.

(ii.) Organismal Contributions

From the soil, another form of uptake could involve plant relationships with mycorrhizal fungi. Mycorrhizal fungi can contain MPs from various ways of uptake from the soil. Due to the close relationships between plant roots and their respective symbiotic organisms in the soil, mycorrhizal fungi can easily transfer MPs during the exchange of nutrients and other particles. Additionally, other soil organisms such as earthworms can ingest MPs and after their death or after releasing waste, plants can uptake these particles through passive uptake from their roots. Other properties of MPs such as their size and surface charge can also affect root ingestion, as larger particles may not be absorbed by root hairs and particles with specific charges can be repelled by charged root hairs [21].

(iii.) Fertilizer Contamination

Plants can also intake MPs from artificial fertilizers used mostly for agricultural purposes. These fertilizers can contain MPs in packaging or be exposed in some step of the process, and ultimately ending up in plant systems. Research has also found that organic fertilizers can contain up to 895 MPs/kg which can be detrimental to plant health and eventually to human health. This can be a range of sizes which risk being further broken down into smaller particles that more easily traverse within soil.

3.2.2 Liquid/Water Uptake

The most common way for plants to uptake microplastics from a liquid vehicle is through the ingestion of contaminated fluid. In agriculture, plants are often irrigated with MP contaminated water, which may be absorbed through passive osmotic or active root drinking processes. Runoff from domestic, industrial, and agricultural activities can make their way into wastewater treatment facilities or directly into farmlands. There, microplastics can escape filtering, particularly smaller (particular sizes that are permeable) particles and fibres [22]. Next, poorly filtered contaminants from the treatment plants can flow into irrigation supply, making their way into soil and plant systems. In addition, natural runoff can siphon existing environmental MPs and circumvent irrigation and water purification facilities.

3.2.3 Air/Environment Uptake

Permeable MPs can transfer into plants through air or gaseous transport. One of these ways is foliar uptake, meaning MPs are deposited on plant surfaces. This less common form of uptake leverages plant aspiration in which MPs are drawn directly through leaf stomata and other surface openings. The estimated effective range of size of this pathway is approximately 0.6-4.8 nm [23].

Once inside the plant, MPs can sometimes make their way into mesophyll tissues, which poses plant health risks as mesophyll tissues are the key organs for photosynthesis and respiration [24]. A study also found that there were dynamic fluctuations in MP uptake attributed to micromorphological structures of the plant surface, where high specific surface areas resulted in maximum MP uptake [25].

While this form of uptake is less common than root uptake, it is still a significant cause for adverse effects in plant processes. Entry into respiratory pores and exposed circulatory channels is the direct contact of MPs as a gaseous vehicle.

The majority of airborne MPs that successfully accumulate on plant surfaces are fibrous because their aerodynamic nature allows them to effectively spread through the air. These MPs make up ~90% of airborne

MPs and can travel distances up to 1000 m by way of wind and rain [26]. Even if these MPs do not enter internal structures, their deposition alone is toxic by way of blocking sunlight and gas exchange, two crucial factors to plant health.

4. Conclusion

As microplastics continue to rise as a growing threat to many forms of biological life, the mechanisms and pathways of uptake in plants also become crucially important to study. MPs in the environment primarily originate from industrial products, but can also infiltrate natural ecosystems through runoff and poorly treated wastewater. Once in the environment, MPs can invade plants through three interfaces. First, plants can uptake MPs from direct solid contact such as absorption through roots, organismal interactions and fertilizer contamination. Next, plants can intake MP-contaminated water originating from various sources. Lastly, by way of atmospheric deposition and wind transport, airborne MPs can traverse through the air and infiltrate the stomata and other surface openings. Understanding how contaminants enter plants is crucial as it can give insight into how ecosystems and food chains are affected as a whole. Through vehicles such as soil, water, and air, plants can absorb and uptake harmful particles that can pose risks to their health and productivity. Thus, in order to mitigate these ramifications, it is essential to focus on reducing industrial pollution and finding sustainable agricultural initiatives that can improve plant wellbeing in the short and long term.

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