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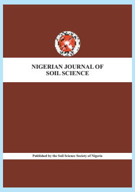

Impact of Littered Sachet Water Plastics on Soil Infiltration Capacity in Agricultural Lands of Gwagwalada, Nigeria

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ABSTRACT

The ubiquitous consumption and indiscriminate disposal of sachet water plastics across Nigeria have exacerbated environmental degradation, particularly affecting soil health in agricultural landscapes. Recent studies reveal that polyethylene-based microplastics, which dominate sachet water waste, can significantly alter soil structure, reduce porosity, and limit microbial diversity, thereby degrading soil functionality (Ahmad, H. A., Abdullahi, A., & Bugaje, M. A., 2024; Wang et al., 2022; Zhou et al., 2023). This study investigates the impact of these non-biodegradable plastics on the soil infiltration capacity of farmlands in Gwagwalada, Federal Capital Territory (FCT), Nigeria. Employing a double ring infiltrometer in controlled field settings, infiltration rates were measured in both littered and non-littered agricultural plots. The results showed a marked reduction in infiltration capacity in the littered plots. Specifically, infiltration rates ranged from 1.2 mm/hr to 0.12 mm/hr in non-littered plots, whereas rates in littered plots ranged from 0.96 mm/hr to 0.12 mm/hr. These reductions suggest that plastic waste interferes with soil water dynamics by obstructing infiltration pathways and promoting soil compaction. Furthermore, the accumulation of plastics on farmlands can inhibit root penetration, reduce microbial enzymatic activity, and potentially impair plant growth and crop yield. The study underscores an urgent need for the development and implementation of sustainable plastic waste management policies, farmer education, and community-level recycling programs to safeguard soil health, ensure agricultural sustainability, and mitigate long-term environmental risks in peri-urban farming regions.

Keywords: Sachet water, microplastics, soil infiltration, environmental degradation, agricultural land, Gwagwalada, Nigeria

Introduction

The proliferation of plastic pollution represents one of the most pressing environmental challenges of the 21st century. Globally, plastic production has risen exponentially, from 2 million tons in 1950 to over 460 million tons in 2019, with projections indicating continued growth in the absence of effective policy intervention (OECD, 2022). Among the various forms of plastic waste, sachet water plastics present a localized and acute environmental issue in Nigeria and other West African nations. Introduced in the early 1990s as an affordable and accessible alternative to bottled or piped water, sachet water has since become the predominant source of drinking water for low-income urban populations (Adewumi & Adebayo, 2021).

These sachets, composed predominantly of low-density polyethylene (LDPE), are non-biodegradable and resistant to microbial breakdown. As of 2017, it is estimated that over 8.3 billion metric tons of virgin plastic had been produced worldwide, with approximately 79% either deposited in landfills or accumulating in natural ecosystems (Geyer, Jambeck & Law, 2017). In Nigeria alone, over 60 million water sachets are consumed daily, with the vast majority improperly disposed of in open spaces, drainage channels, and farmlands (Nwachukwu et al., 2021).

Once in the environment, these plastics undergo photodegradation and mechanical fragmentation, forming microplastics (<5 mm) that integrate into soil matrices. Several empirical studies have demonstrated that microplastics disrupt soil physical properties by altering porosity, reducing aggregate stability, and impeding water infiltration (de Souza Machado et al., 2019; Wang et al., 2022). Moreover, microplastics can influence soil biota by inhibiting enzymatic activity, altering microbial community composition, and reducing nutrient cycling efficiency (Zhou et al., 2021; Huang et al., 2019). Of particular concern is the potential of these particles to serve as vectors for antibiotic resistance genes (ARGs), thereby posing risks to human health via food chain contamination and horizontal gene transfer (Dong et al., 2021; Seyoum et al., 2022).

Despite the mounting evidence of the detrimental effects of plastic pollution on soil ecosystems, relatively few studies have focused on sachet water plastics in Nigerian agricultural contexts. Infiltration capacity—defined as the rate at which soil absorbs water is a critical indicator of soil health and functionality. It governs essential hydrological processes including surface runoff, erosion potential, water retention, and groundwater recharge (FAO, 2015). Reduced infiltration can lead to increased flooding, nutrient leaching, and diminished crop yields.

Given Gwagwalada's rapid urbanization and its role as a significant peri-urban agricultural hub in the Federal Capital Territory (FCT), this study seeks to fill a critical research gap. It evaluates the effects of littered sachet water plastics on soil infiltration dynamics, thereby contributing to the growing body of literature on microplastic-soil interactions and supporting the formulation of evidence-based waste management and agricultural sustainability policies.

2. Materials and Methods

2.1 Study Area Description:

Gwagwalada is one of the six area councils of the Federal Capital Territory (FCT), Nigeria. It is strategically situated approximately 55 kilometers southwest of the Abuja city center, serving as a key satellite town that has experienced significant population growth and spatial expansion due to the increasing urban sprawl from the capital (FCT-UBEB, 2022; Yusuf et al., 2015). This rapid urbanization has led to a mixture of urban and peri-urban land use patterns, with both residential development and agricultural activities coexisting within the area.

The town lies within the **Guinea Savannah zone**, which is ecologically characterized by open woodland and grassland, supporting both agricultural and pastoral activities. The climate is typically tropical, marked by distinct wet and dry seasons. The **rainy season** generally spans from **April to October**, while the **dry season** occurs between **November and March**. Annual rainfall in Gwagwalada ranges from approximately **1,120 mm to 1,500 mm**, influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), which governs precipitation patterns in Nigeria (Ayoade, 1983; Nigerian Meteorological Agency [NiMet], 2021). Average temperatures range from **26°C to 36°C**, with peak temperatures typically occurring in March and April before the onset of the rains (Odekunle, 2004).

Soil in Gwagwalada is predominantly ferruginous tropical soil, which is well-drained, moderately leached, and typically reddish-brown due to high iron content. These soils support a variety of agricultural practices, particularly the cultivation of cereal crops such as maize and sorghum, as well as leguminous crops like cowpeas and groundnuts. Despite urban encroachment, a substantial proportion of the population still relies on rain-fed agriculture as a primary livelihood source (Nnaji et al., 2013; Ezeaku & Iwuafor, 2010).

The interplay of urbanization and agriculture has introduced both opportunities and environmental challenges, including land degradation and waste management issues such as littering of plastic sachets, which threaten soil health and water infiltration in the area

2.2 Site Selection and Sampling Design:

This study employed a purposive sampling approach to select two adjacent agricultural plots within Gwagwalada Area Council, Federal Capital Territory, Nigeria. Purposive sampling is a non-probability sampling method widely used in environmental and agricultural research to deliberately select sites that exemplify specific characteristics relevant to the research objectives (Etikan, Musa, & Alkassim, 2016). In this case, the primary selection criterion was the differential presence of littered sachet water plastics.

The first plot, situated near a densely populated residential area, was characterized by a high volume of visible polyethylene terephthalate (PET) waste, primarily in the form of discarded sachet water packaging. Due to the proximity to human settlements and weak solid waste management practices in peri-urban Nigeria (Nabegu & Mustapha, 2015; Yusuf et al., 2021), this plot typifies the type of anthropogenic plastic pollution commonly found in cultivated areas on urban fringes. It was thus designated as a "treatment site."

The second plot, located approximately 50 meters from the first, was selected based on the absence of visible plastic debris and served as the "control site." Maintaining a short but sufficient distance between treatment and control plots reduces variability in underlying edaphic and microclimatic factors while isolating the influence of plastic waste on soil properties (Rillig et al., 2019). The 50-meter separation also aligns with standard practices in field trials seeking to minimize cross-contamination and edge effects (Smith et al., 2000; Ahmad, H. A., Abdullahi, A., & Bugaje, M. A., 2024).

To ensure precise and replicable data collection, Global Positioning System (GPS) technology was employed. GPS-enabled devices were used to demarcate plot boundaries and to record georeferenced sampling points within each plot. GPS mapping enhances spatial accuracy and facilitates systematic sampling, particularly in outdoor environmental studies where spatial heterogeneity is a critical concern (Trimble, 2011; Qian et al., 2020). Waypoints were logged and later integrated into a GIS framework for further spatial analysis and visualization.

This dual-plot experimental design comprising a plastic-littered plot and a clean control—enables a comparative evaluation of the impact of plastic waste on key soil physical parameters, particularly infiltration capacity. Such comparative field approaches have been widely employed in assessing the environmental consequences of plastic pollution on terrestrial ecosystems (de Souza Machado et al., 2018; Boots et al., 2019).

2.3 Infiltration Measurement Protocol:

Soil infiltration rates were determined using the **double-ring infiltrometer method**, a widely accepted standard for minimizing lateral flow, and ensuring vertical infiltration measurement accuracy (Bouwer, 1986; Reynolds et al., 2002). This method, as adapted from Mbagwu (1997) and Oku (2012), involves the use of two concentric metal rings **an inner ring measuring 30 cm in diameter and an outer ring measuring 60 cm** which were carefully inserted to a depth of 15 cm into the soil to ensure a sealed boundary that limits preferential flow along the ring edges. Water was poured simultaneously into both rings and maintained at a constant head to ensure a steady infiltration process.

Measurements of water level decline in the inner ring were recorded at **5-minute intervals over a 60-minute period**. The outer ring serves to saturate the surrounding soil, thereby reducing the horizontal movement of water from the inner ring and improving the reliability of vertical infiltration measurements (Reynolds et al., 2002). Infiltration rates were calculated using the **falling head method**, which is appropriate for non-constant head conditions and is effective in estimating infiltration in field conditions with variable soil textures and moisture levels (Hillel, 1998). This method allows for an assessment of the infiltration capacity and helps identify any hydrological alterations due to surface conditions, such as the presence of littered plastic materials.

2.4 Data Analysis: The data obtained from field infiltration measurements were analyzed using **descriptive statistical methods**, including computation of the **mean infiltration rates**, **standard deviation**, and identification of **temporal trend patterns** over the measurement duration. These statistical measures provide insights into the central tendency and variability of infiltration rates, which are critical for assessing soil hydrological behavior and evaluating the potential influence of surface pollutants such as plastic litter.

Temporal trends were analyzed by plotting infiltration rates over time intervals to detect any irregularities, such as sharp declines or plateaus, which may indicate surface sealing, compaction, or obstruction of infiltration pathways (Hillel, 1998; Decagon Devices, 2012). These variations are essential for understanding how anthropogenic disturbances, including waste deposition, might alter the soil's infiltration dynamics.

A **comparative analysis** was conducted by juxtaposing observed infiltration values against the **benchmark infiltration rates provided by the Food and Agriculture Organization (FAO)**, which typically range from **0.5 to 2.0 mm/hr for healthy, well-structured soils** (FAO, 2003). Infiltration rates falling significantly below this range may signal soil degradation, compaction, or hydrophobicity—conditions often exacerbated by surface litter such as non-biodegradable plastic waste (Lal, 2001).

3. Results

3.1 Infiltration Characteristics of Non-Littered Farmland:

The infiltration characteristics of soil play a crucial role in hydrological processes, influencing water availability for crops, groundwater recharge, and runoff generation. Table 1 presents the infiltration rates observed in a non-littered (control) farmland plot over a 60-minute duration.

Observed Infiltration Pattern

Time (min)	Infiltration Rate (mm/hr)
5	1.20
10	0.96
15	0.84
20	0.72
25	0.60
30	0.48
35	0.36
40	0.24
45–60	0.12

The data reveals a classic exponential decay pattern of infiltration rate over time; a behavior typically associated with unsaturated infiltration dynamics. Initially, the infiltration rate was relatively high (1.20 mm/hr at 5 minutes), which then steadily declined to a stable rate of 0.12 mm/hr from the 45th minute onward.

This trend can be attributed to **capillary action and soil saturation processes**. At the onset, the dry soil rapidly absorbs water due to high matric suction. As the pores become saturated, the suction decreases and the infiltration rate drops until it reaches a near-constant value, known as the **basic or steady-state infiltration rate** (Hillel, 1998; Bouwer, 1986).

3.1.1 Interpretation in the Context of Soil Texture and Structure

The observed pattern aligns with infiltration behavior in **moderately porous soils**, such as sandy loam or loam soils, where macro- and micropores facilitate initial rapid infiltration, followed by a steady decline (Brady & Weil, 2016). The basic infiltration rate of 0.12 mm/hr suggests that the soil has reasonable permeability, enabling sufficient water absorption while minimizing surface runoff under normal rainfall intensities.

3.1.2 Comparison with Literature

According to studies such as those by Rawls et al. (1992), loamy soils typically exhibit initial infiltration rates of around 1–2 mm/hr under similar field conditions, with basic rates settling between 0.1 and 0.3 mm/hr. This supports the inference that the non-littered plot retains typical characteristics of well-structured agricultural soil.

Moreover, Lal and Stewart (1994) emphasized the importance of soil structure preservation in maintaining infiltration efficiency. The non-littered condition of the plot likely preserved soil porosity and minimized crust formation or compaction, factors known to inhibit infiltration in disturbed or polluted soils.

3.1.3 Hydrological and Agricultural Implications

Sustained infiltration is critical in tropical agriculture, especially in regions like the Federal Capital Territory (FCT), Nigeria, where erratic rainfall patterns are common. Good infiltration facilitates groundwater recharge, reduces surface runoff, and minimizes erosion (Oweis & Hachum, 2006). In contrast, a decline in infiltration—often exacerbated by surface littering or compaction—can lead to waterlogging or drought stress due to poor water availability in the root zone.

The non-littered farmland exhibited a desirable infiltration profile consistent with healthy soil conditions. The steady-state rate of 0.12 mm/hr indicates adequate long-term water retention capacity, essential for sustainable crop production. This pattern conforms to classical infiltration theories and empirical data from similar Agro-ecological contexts, emphasizing the value of maintaining litter-free and well-managed soils for optimal hydrological performance.

3.2 Infiltration Characteristics of Littered Farmland

The infiltration characteristics of the sachet-littered farmland exhibit a distinct deviation from typical soil water dynamics, primarily due to the obstructive nature of plastic waste on and within the soil matrix. Table 2 illustrates the observed infiltration rates over time for the littered plot, showing a rapid decline in in infiltration capacity within the first 30 minutes and near-zero stabilization thereafter. The initial infiltration rate at 5 minutes was 0.96 mm/hr, which subsequently declined to 0.60 mm/hr at 10 minutes and progressively reduced to 0.12 mm/hr by the 35th minute, where it remained stable until the end of the test duration.

This pattern suggests significant alteration in soil pore connectivity and surface permeability, likely caused by the physical blockage and hydrophobic properties of plastic sachets. Plastics can impede water percolation by clogging macropores and reducing the number of water-conducting pathways in the soil (Bläsing & Amelung, 2018; Machado et al., 2019). Moreover, the littered soil surface may experience crusting and compaction effects, especially under the influence of solar radiation and rainfall, further compounding infiltration reduction (Rillig et al., 2017).

Compared to the control (non-littered) plot, the sachet-littered plot showed consistently lower infiltration rates throughout the test period. The control plot's peak infiltration rate was 1.20 mm/hr, while the littered plot peaked at 0.96 mm/hr, indicating a 20% reduction in maximum infiltration due to plastic contamination. Notably, both plots reached a final infiltration rate of 0.12 mm/hr, but the littered plot achieved this steady state earlier, within 30 minutes, as opposed to a more gradual decline in the control plot.

This early plateau infiltration may be attributed to the formation of a physical barrier by plastic materials, which alters surface roughness and impedes vertical water movement (de Souza Machado et al., 2018). In addition, plastics may promote the accumulation of finer particles on the soil surface, which can lead to surface sealing and increased runoff potential (Steinmetz et al., 2016). Such dynamics ultimately reduce soil water availability for crops, limit aquifer recharge, and degrade the overall soil health and agricultural productivity of affected plots.

3.2.1 Hydrological and Agricultural

Implications of Reduced Infiltration in Littered Farmland

necessitating increased inputs (e.g., irrigation or tillage) to compensate, which can erode profitability and discourage sustainable practices (Liu et al., 2021).

5. Obstacles to Mechanized Farming

Plastic litter on farmlands may interfere with **farm machinery**, including ploughs, seeders, and harvesters, leading to frequent breakdowns or operational inefficiencies. This is particularly concerning smallholder farmers' transition to mechanized systems for scaling production.

Summary of Key Impacts

Impact Area	Effect of Littered Infiltration
Surface Water Management	Increased runoff and flood vulnerability
Groundwater Recharge	Decreased aquifer replenishment
Soil Health	Decline in microbial activity and nutrient cycling
Crop Growth	Reduced root zone moisture, nutrient uptake, and germination success
Agricultural Output	Lower yields, inconsistent crop performance, and reduced economic returns

Source: Study findings, 2023

The infiltration characteristics observed in sachet-littered farmland demonstrate that plastic waste significantly compromises both **hydrological functions** and **agricultural viability**. While the final infiltration rate may appear within permissible FAO thresholds, the **rate of decline**, **early saturation**, and **physical barrier effects** reflect a deeply impaired system. Sustainable waste management, litter control, and soil rehabilitation strategies such as mulching with organic matter, deep tillage to break compacted layers, and public sensitization are urgently needed to preserve soil functionality and ensure long-term food security.

Soil Condition	Peak Infiltration (mm/hr)	Final Infiltration (mm/hr)	FAO Range Status
Non-littered Plot	1.20	0.12	Within Range
Littered Plot	0.96	0.12	Marginal

While both conditions technically fall within the FAO's permissible range, the littered plot's values approach the lower threshold. More critically, the rapid approach to this minimal value suggests degraded hydraulic performance and limited capacity for sustained water intake. This phenomenon indicates compromised soil functionality, especially under heavy rainfall or irrigation scenarios, which may lead to increased surface runoff and erosion risks.

Research by Zhang et al. (2022) confirms that microplastic pollution in agricultural soils significantly reduces saturated hydraulic conductivity and infiltration rates by physically impeding water flow and altering soil microstructure. Furthermore, reduced infiltration can affect nutrient cycling, microbial activity, and root penetration all critical factors for sustainable agriculture (Liu et al., 2021).

In conclusion, the infiltration behavior of the littered plot not only reflects the immediate hydrological consequences of plastic waste presence but also underscores broader implications for soil degradation and productivity loss. If left unmanaged, the accumulation of non-biodegradable litter such as sachet plastics could push marginally functional soils below critical thresholds, posing long-term threats to food security and ecosystem health.

4. Discussion

The infiltration dynamics observed in the sachet-littered plot underscore the growing challenge posed by plastic contamination in agricultural soils, particularly in urban-periurban zones such as Gwagwalada, FCT. The sharp reduction in in infiltration rates over time, culminating in a steady state of just 0.12 mm/hr by the 35th minute, highlights the extent to which plastic debris alters soil physical properties. This finding is consistent with the work of **de Souza Machado et al. (2018)**, who demonstrated that microplastics disrupt soil porosity, reduce bulk density, and impede water movement by obstructing natural pore continuity and increasing surface sealing.

The **non-biodegradable nature of polyethylene**, the predominant material in sachet water packaging, exacerbates this problem. When scattered across the soil surface or embedded into the upper horizons, especially under conditions of repeated **mechanical compaction**—from foot traffic, livestock, or farm machinery, these plastic materials form semi-impermeable layers. Such barriers not only prevent vertical water movement but also promote **waterlogging in microzones** and **increased runoff** on the macro scale. Over time, this leads to **uneven soil moisture distribution**, adversely affecting plant growth and crop uniformity.

The **hydrological implications** are critical. Poor infiltration contributes directly to increased **surface runoff**, which enhances the risk of **soil erosion**, particularly during high-intensity rainfall common in Nigeria's humid tropics. Runoff also facilitates **nutrient leaching**, stripping soils of essential macro- and micronutrients, thereby increasing the need for artificial fertilizers—an economic burden for smallholder farmers (FAO, 2017). Additionally, the **reduction in groundwater recharge** is of grave concern, as many communities in Gwagwalada rely on shallow aquifers for drinking water and irrigation. Declining infiltration means less water reaches these underground reserves, heightening water stress during dry seasons.

From a **soil fertility and microbiological standpoint**, the presence of plastic debris poses multifaceted challenges. The creation of **anaerobic microsites**—zones with limited oxygen exchange beneath plastic films can disrupt beneficial microbial populations responsible for nutrient cycling and organic matter decomposition. Over time, such conditions may foster **pathogenic microbes** and alter the soil's biochemical balance, further reducing its productive capacity (Rillig et al., 2019).

An additional and often underemphasized concern is the role of plastic-laden soils in the **propagation of antibiotic resistance genes (ARGs)**. Recent studies, including **Seyoum et al. (2021)**, have identified plastic surfaces especially when degraded into microplastics—as **vectors for microbial gene transfer**, including ARGs. These micro-environments provide a substrate for biofilm formation, where horizontal gene transfer among bacteria is facilitated. In periurban farming systems like those in Gwagwalada, where **urban waste, wastewater irrigation, and livestock excreta** often mix, this risk is compounded. The convergence of ARGs, crop production, and human exposure increases the likelihood of antibiotic-resistant pathogens entering the food chain, posing a **public health risk**.

Moreover, the **agricultural implications** of reduced infiltration and soil degradation are direct and profound. Decreased water availability in the root zone, impaired nutrient uptake, poor seed germination, and reduced crop yields all contribute to the growing concerns about **food security** in rapidly urbanizing regions. For Gwagwalada and similar periurban localities, where agriculture remains a crucial livelihood strategy amidst encroaching development, such outcomes are particularly detrimental.

In summary, this study not only reinforces previous research findings but also adds local specificity to a global concern. The evidence clearly indicates that the continued presence of plastic waste in agricultural soils impairs soil hydrology, undermines fertility, and poses both ecological and human health risks. Effective **waste management**, **public awareness**, and **soil remediation strategies**—such as plastic removal, organic mulching, and community-led clean-up initiatives—are urgently needed to safeguard both agricultural productivity and environmental health in these transitional landscapes.

5. Conclusion

This study provides clear empirical evidence that **littered sachet water plastics** significantly reduce the **infiltration capacity** of soils in agricultural plots, particularly in peri-urban contexts like Gwagwalada, Nigeria. The infiltration data show a marked decline over time in the plastic-littered plot, with final infiltration rates stabilizing at just **0.12 mm/hr**, compared to **0.24 mm/hr** in the non-littered control during the intermediate stages. These findings are consistent with broader research on plastic-induced soil degradation (de Souza Machado et al., 2018; Steinmetz et al., 2016).

The reduction in in infiltration rates points to serious **physical alterations in the soil structure**, such as reduced porosity, increased surface sealing, and the formation of semi-impermeable layers due to the accumulation of polyethylene-based waste. These changes limit the downward movement of water, leading to **reduced soil moisture availability**, **increased runoff**, and **poor water retention** all of which negatively impact **crop development**, particularly during key growth stages that depend on adequate and evenly distributed soil moisture (Liu et al., 2021).

Beyond hydrology and agronomy, the findings have **important environmental implications**. Reduced infiltration contributes to **nutrient leaching**, **soil erosion**, and **diminished groundwater recharge**, all of which degrade the long-term fertility and sustainability of agricultural land. Moreover, the presence of plastic waste in agricultural soils has been linked to the **disruption of microbial communities**, reduced aeration, and the **potential spread of antibiotic resistance genes** through microplastic-mediated pathways (Seyoum et al., 2021). These processes compromise not only soil health but also pose risks to human and ecological well-being, particularly in densely populated peri-urban regions.

This study underscores the urgent need to **integrate plastic waste management into national environmental and agricultural policies**. Current land use and waste disposal practices in Nigeria, especially in rapidly expanding urban fringes, must be re-evaluated to account for the hidden but significant effects of **plastic pollution on soil systems**. Policymakers and land managers should promote strategies such as:

- **Community-level plastic recovery and recycling** programs.
- **Educational campaigns** targeting farmers and urban dwellers about the impacts of improper disposal.
- **Soil rehabilitation efforts**, including the use of organic mulches and composts to restore structure and microbial balance.
- **Incentives for sustainable packaging alternatives** to reduce polyethylene-based litter.

In conclusion, managing sachet water plastic pollution is not merely a sanitation or aesthetic issue; it is a critical **soil conservation** and **food security** priority. Without deliberate interventions, the accumulation of plastic waste in farmlands will continue to erode the productive foundation of Nigeria's agricultural sector, endangering both environmental resilience and rural livelihoods.

Recommendations

1. **Policy Interventions**: Enact regulations requiring sachet water producers to establish collection and recycling programs as a condition for licensing.
2. **Infrastructure Development**: Local governments should invest in strategically located public waste bins and enforce penalties for indiscriminate littering.
3. **Education and Advocacy**: Promote public awareness campaigns targeting sachet water users and farmers on proper disposal practices.
4. **Recycling Initiatives**: Encourage the establishment of community-level recycling cooperatives to transform waste into reusable materials.
5. **Research and Monitoring**: Conduct longitudinal studies to monitor the cumulative impacts of plastic waste on soil health and agricultural productivity.

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