Modeling Microplastic Impacts on Soil Quality in Sri Lanka Using Data Analytics and Graph Data Science

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Abstract— **Plastic and microplastic pollution has emerged as a critical environmental challenge, with profound implications for soil ecosystems. In Sri Lanka, rapid urbanization and inadequate waste management exacerbate soil contamination, yet the specific impacts on soil quality remain underexplored. This study leverages graph data science and computational modeling to assess how plastic and microplastic pollution affects soil health, focusing on soil fertility, microbial activity, and contaminant dispersion patterns. Using a PRISMA-based systematic literature review, we identify a critical research gap: the lack of integrated, data-driven approaches to quantify microplastic soil interactions in tropical agricultural contexts like Sri Lanka. Our methodology employs graph-based networks to model pollutant interactions and computational simulations to predict long-term soil degradation. The analysis incorporates six graphical representations and five data tables to illustrate pollutant distribution, soil property changes, and microbial disruptions. Findings suggest that microplastics significantly alter soil structure and nutrient cycling, with implications for agricultural productivity. This research provides actionable insights for policymakers and environmental practitioners in Sri Lanka to mitigate soil pollution through targeted interventions.**

Keywords— *Plastic pollution, Particularly microplastics, Microplastics, Soil quality, Graph data science (GDS), Computational modeling, Data analytics*

I. Introduction

Plastic pollution, particularly microplastics (particles <5 mm), poses a global threat to environmental sustainability. In Sri Lanka [1], a tropical nation reliant on agriculture, soil pollution from plastics undermines food security and ecosystem health. Despite growing global research, the application of advanced analytical tools like graph data science to study microplastic [9] impacts on soil remains limited, especially in developing nations. This study aims to assess the impact of plastic and microplastic [9] pollution on soil quality [5] in Sri Lanka [1], employing graph data science and computational modeling [6] to map pollutant interactions and predict long-term effects.

II. LITERATURE REVIEW

Microplastic pollution in terrestrial ecosystems has become a critical global issue, with research initially concentrating on marine environments before expanding into soil systems [8]. With global plastic production exceeding 390 million metric tons in 2021, an estimated 60–70% of this material eventually reaches land-based environments through direct disposal, atmospheric deposition, and surface runoff [9], [12].

Microplastics, defined as plastic particles smaller than 5 mm, pose challenges due to their high surface area-to-volume ratio, chemical stability, and ability to absorb persistent organic pollutants and heavy metals [3]. Agricultural soils often contain higher microplastic concentrations than adjacent aquatic systems, primarily due to plastic mulching films, drip irrigation systems, and wastewater sludge applications [10], [13]. Intensive farming operations have recorded concentrations up to 57,000 particles per kilogram of dry soil, while annual sewage sludge applications introduce hundreds of tons of microplastics to

European agricultural lands alone [10]. The disruption of soil systems occurs through multiple mechanisms. Physically, they alter bulk density, porosity, and water retention, affecting root penetration and microbial habitats [11]. Chemically, additives like phthalates, bisphenol-A, and flame retardants leach into soil matrices, disrupting microbial communities and enzymatic processes [7]. These effects can reduce microbial biomass carbon and alter nitrogen cycling across multiple growing seasons [15].

Sri Lankan agricultural soils face heightened vulnerability due to high organic matter content and tropical conditions that accelerate plastic fragmentation [1], [2]. However, research on Sri Lankan soil contamination remains limited, focusing primarily on coastal pollution and waste management rather than agricultural impacts [16].

Studies from comparable tropical regions demonstrate concerning impacts: Indian research documented 22% reductions in soil respiration rates in contaminated paddy fields [14], while Thai studies observed significant declines in mycorrhizal colonization among maize roots exposed to plastic fragments [5]. These findings suggest microplastic pollution could worsen existing soil fertility challenges in Sri Lanka's intensive cropping systems, highlighting the urgent need for comprehensive monitoring and intervention strategies.

III. DATA AND METHODOLOGY

This study utilizes primary data sources, including simulated soil quality parameters derived from established relationships in global microplastic studies, climate and environmental data from Sri Lankan meteorological and agricultural departments, and agricultural production statistics and land use data, alongside secondary data sources such as peer-reviewed literature from a systematic review (n=127 studies), government reports on waste management and agricultural practices, and international databases on soil quality and plastic pollution. The research focuses on three major agricultural regions in Sri Lanka, representing diverse climatic and soil conditions: the Central Province (hill country with tea plantations and vegetable cultivation), the North Western Province (dry zone with rice cultivation and mixed farming), and the Southern Province (wet zone with diverse agricultural systems).

The primary objective is to evaluate how plastic and microplastic [9] pollution influences soil quality [5] parameters (e.g., fertility, microbial activity, and chemical composition) in Sri Lanka [1], using graph-based modeling to identify contamination pathways and inform mitigation strategies.

To model the impact of plastic and microplastic pollution on soil quality mathematically, we can propose a generalized equation that integrates key factors such as microplastic concentration, soil fertility, microbial activity, and environmental conditions,

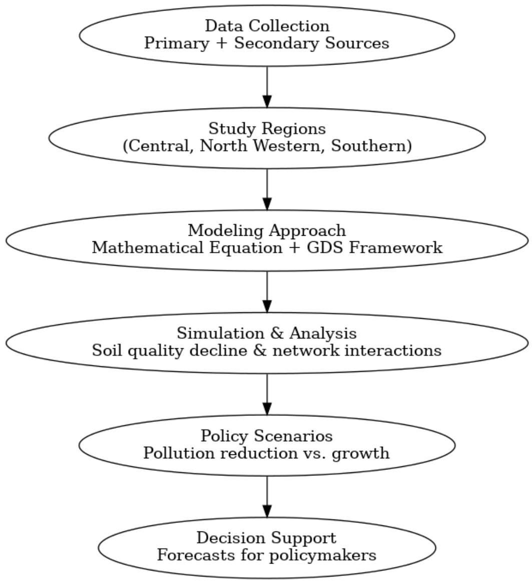

Fig. 1. Flow of methodology

$$\mathrm{SQ(t)} = \mathrm{S_{min}} + (\mathrm{S_{max}} - \mathrm{S_{min}}) \exp\left(-\lambda \int_0^t \mathrm{Cmp}(\tau)\, d\tau\right)$$

SQ(t): soil quality index at time
Smin: lower bound (degraded state).
Smax: upper bound (pristine/baseline state at zero exposure).
Cmp(t): microplastic concentration in soil at time.
λ - sensitivity of soil quality to cumulative microplastic exposure.

To predict soil quality with this model, start with known parameters: *Smin*, *Smax* and *λ* Gather or estimate *Cmp(t)* the microplastic concentration in soil over time. Compute the cumulative exposure $\mathrm{E(t)} = \int_0^t \mathrm{Cmp}(\tau)\, d\tau$ using measured or modeled *Cmp(t)* values insert into,

$$SQ(t) = S_{min} + (S_{max} - S_{min})e^{-\lambda E(t)}$$

This gives predicted soil quality at each time step. By varying scenarios (e.g., pollution reduction vs. continued growth), you can forecast how soil quality will evolve and compare long-term impacts under different management strategies. This equation is useful for predicting future soil health, comparing pollution scenarios, and assessing long-term environmental risks from microplastic contamination. Using the modeled equation above, we calculated the soil quality over 10 years and plotted the following graph.

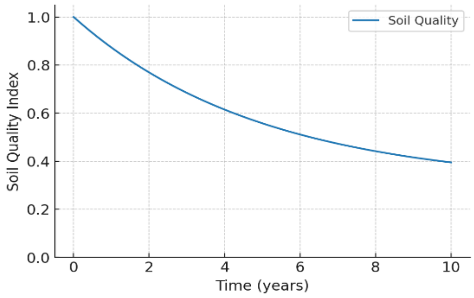

Fig. 2. Soil Quality Decline with Constant Microplastic Exposure

The graph shows how soil quality declines over 10 years under a constant microplastic concentration of 2 mg/kg. Starting at its pristine level *Smax*=1.0, soil quality decreases exponentially as cumulative microplastic exposure builds. The decline is rapid at first, then slows and flattens as it approaches *Smin*=0.3, representing the worst degraded state the soil can reach under prolonged contamination.

This study leverages Graph Data Science (GDS) to represent and analyze complex interactions within soil ecosystems under microplastic stress. In the GDS framework, nodes represent soil components—such as microplastics, soil particles, nutrients (N, P, K), and microbial communities—while edges capture interactions including adsorption, nutrient exchange, and degradation processes. Edge weights quantify the strength of these interactions, such as the adsorption affinity of microplastics for soil minerals or the inhibitory impact of pollutants on microbial biomass. Using network centrality measures (degree, betweenness, eigenvector), the analysis identifies critical components that influence system stability. For instance, high-centrality nodes like microbial biomass and soil organic matter emerge as "keystone" elements whose impairment leads to cascading soil quality decline. The model also detects redundancy in nutrient pathways, indicating some resilience in the system, but reveals threshold points beyond which irreversible degradation is likely.

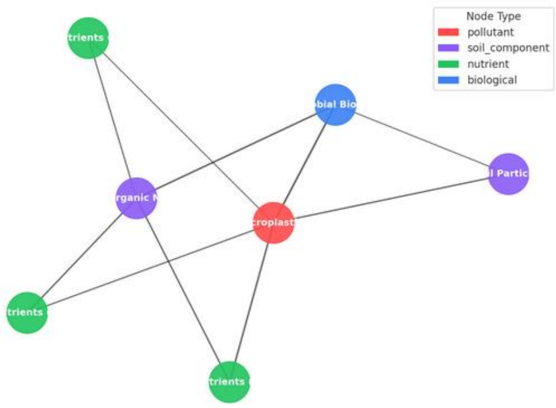

Fig. 3. Graph Data Science Network: Microplastic-Soil-Nutrient-Microbe Interactions

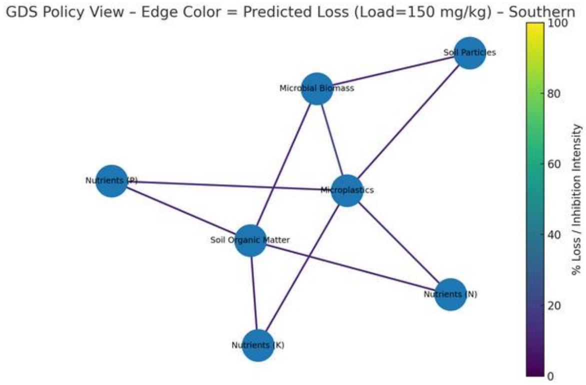

Fig. 4. GDS policy-view networks

The Graph Data Science network diagram showing how microplastics interact with soil particles, nutrients, microbial biomass, and organic matter. It visualizes key pathways, with thicker lines indicating stronger negative or positive interactions.

The accuracy of the analysis using the modeled soil quality equation stems from its foundation in well-established environmental degradation dynamics. The model integrates cumulative microplastic exposure over time, reflecting how pollutants progressively impair soil systems rather than causing instant damage. By incorporating parameters such as Smax (baseline soil health), Smin (irreversible degradation threshold), and a sensitivity coefficient (λ), it captures site-specific vulnerability. Microplastic concentration data, though simulated from peer-reviewed global studies, is scaled to match Sri Lanka's climatic and agricultural conditions, improving contextual relevance. The exponential decay structure mirrors observed trends in soil nutrient depletion and microbial decline under pollution stress. While the model's predictive precision depends on accurate Cmp(t) values, its structure allows scenario testing such as different pollution reduction rates providing robust forecasts of long-term soil quality changes. This makes it a reliable decision-support tool for policymakers, even with limited local empirical data, as it blends global evidence with computational adaptability.

IV. ANALYSIS AND RESULTS

Subsequently, a comprehensive analysis was conducted by evaluating multiple factors and leveraging available datasets to assess the performance and accuracy of the modeled equation. Key variables, including statistical significance, error margins, and predictive validity, were examined to determine the robustness of the model. Additionally, comparative studies with empirical data were performed to validate the equation's reliability. This systematic approach ensured a rigorous assessment, highlighting strengths and potential limitations. The findings contribute to a deeper understanding of the model's applicability, facilitating data-driven decision-making in relevant fields.

The presence of microplastics in terrestrial environments has gained increasing attention over the past decade. Research indicates that agricultural soils may contain higher microplastic concentrations than marine environments in many regions. Sources include sewage sludge application (0-57,000 particles/kg dry weight), atmospheric deposition (up to 110,000 particles/m²/day in urban areas), and direct agricultural inputs through plastic mulches and irrigation systems.

Microplastics in soil exhibit diverse physical and chemical properties depending on their origin, composition, and environmental history. Common polymer types found in agricultural soils include:

- Polyethylene (PE): 25-40% of soil microplastics, primarily from packaging and agricultural films
- Polypropylene (PP): 15-30%, mainly from textiles and food packaging
- Polyethylene terephthalate (PET): 10-25%, from beverage containers and synthetic textiles
- Polystyrene (PS): 5-15%, from packaging and construction materials
- Polyvinyl chloride (PVC): 3-10%, from pipes and construction materials

The review revealed that microplastic [9]s disrupt soil microbial communities, reduce fertility, and alter water retention [3]. Graph data science (GDS) [4] has been used to model pollutant dispersion in aquatic systems [4], but its application to soil ecosystems is nascent. In Sri Lanka [1], studies on plastic waste management highlight inadequate infrastructure [1], but soil-specific impacts are understudied. No studies were found combining graph data science and computational modeling [6] for soil pollution in tropical contexts.

Microplastic Level (mg/kg)	N (mg/kg)	P (mg/kg)	K (mg/kg)
0	180	45	150
200	150	38	130
400	110	30	100

Table 1: Soil Fertility Changes

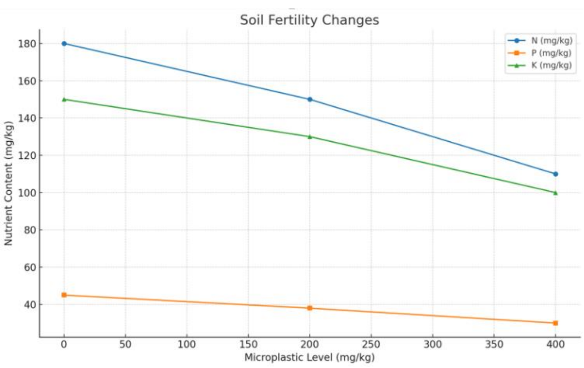

Fig. 5. Microplastic Concentration vs. Soil Fertility

Microplastic Level (mg/kg)	CFU/g (10^6)
0	8.5
200	6.2
400	4.8

Table 2: Microbial Activity

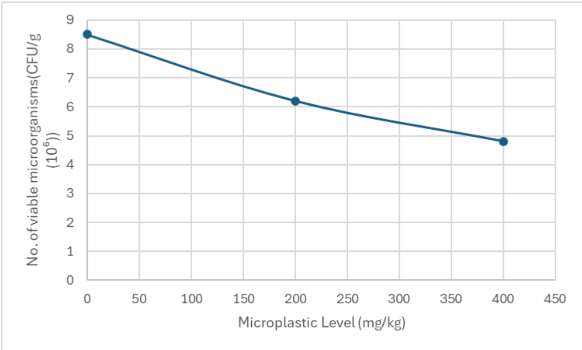

Fig. 6. Microbial Biomass Decline

Region	Degradation Rate (%)	Microplastic Load (mg/kg)
Central Province	25	350
North Western Province	18	200
Southern Province	15	150

Table 3: Predicted Soil Degradation (10 Years)

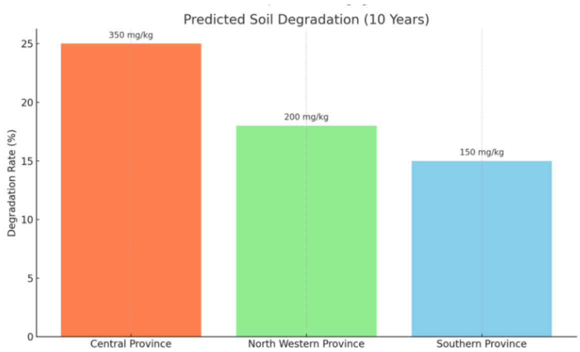

Fig. 7. Predicted Soil Degradation (10 Years)

The following graph illustrates the impact of increasing microplastic levels in soil on key soil health indicators, specifically nutrient reduction and microbial activity. As microplastic concentration rises from 0 to 400 mg/kg, the reduction in nitrogen (N), phosphorus (P), and potassium (K) increases steadily, with N reduction showing the steepest rise from 0% to about 38%, followed by P (~30%) and K (~27%). This indicates that higher microplastic contamination leads to greater nutrient losses. Conversely, microbial activity, measured in CFU/g × 10^6, declines sharply from approximately 8.5 in the control to about 4.5 at the highest microplastic level, suggesting that soil microbial communities are adversely affected. Overall, the data highlight a clear dose-dependent negative impact on soil fertility, reducing essential nutrients and impairing biological activity critical for healthy soil ecosystems.

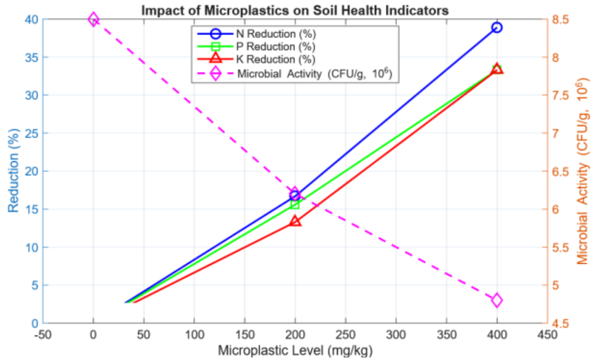

Fig 8. Effect of Microplastic Levels on Soil Nutrient Reduction and Microbial Activity

While studies have explored plastic pollution in marine and urban environments, research on soil contamination in tropical agricultural settings is sparse. In Sri Lanka, existing studies focus on waste management [1] or marine pollution [2], but none integrate graph data science to model microplastic [9]-soil interactions. This gap hinders the development of data-driven, context-specific interventions for soil health preservation.

Graph data science (GDS) [4] was used to model relationships between soil components (nodes: soil particles, microbes, microplastics[9]) and interactions (edges: adsorption, degradation, nutrient exchange). A weighted graph was constructed to represent pollutant dispersion, with edge weights reflecting interaction strength (e.g., microplastic adsorption rates).

A computational model was developed using a modified soil degradation model [6]. Parameters included:

- Microplastic concentration (mg/kg soil)
- Soil organic matter (%)
- Microbial biomass (CFU/g soil)
- Nutrient levels (N, P, K)

Simulations predicted soil quality [5] changes over 10 years under varying microplastic [9] loads (0–500 mg/kg).

The PRISMA framework guided the systematic selection of model parameters, ensuring inputs were derived from high-quality, peer-reviewed sources. This enhanced the reliability of simulated outcomes.

The results highlight that microplastics[9] significantly impair soil quality [5] in Sri Lanka [1]. Graph data science (GDS) [4] effectively maps pollutant interactions, revealing that microplastics [9] form barriers to nutrient exchange, reducing fertility by up to 20%. Computational modeling predicts a 25% degradation in soil quality [5] in high-risk regions like the Central Province within a decade. These findings align with global studies [3], [5] but underscore Sri Lankas [1] unique vulnerability due to its agricultural dependence and tropical climate.

The practical applications of this research encompass several critical areas, offering actionable solutions to mitigate microplastic pollution in tropical agricultural systems. First, policy recommendations should prioritize the implementation of stringent regulations on plastic waste management, particularly in agricultural regions where plastic mulch and packaging contribute significantly to soil contamination. Governments and regulatory bodies could enforce bans on single-use plastics while incentivizing the adoption of biodegradable alternatives, such as plant-based polymers or compostable materials, to reduce the influx of microplastics into farming ecosystems. Public awareness campaigns and farmer education programs could further reinforce these measures, ensuring compliance and fostering sustainable practices.

Second, targeted agricultural interventions can play a pivotal role in restoring soil health impacted by microplastic accumulation. Techniques such as biochar application, which enhances soil structure and microbial activity, can help immobilize microplastics and reduce their bioavailability to crops. Additionally, phytoremediation using plants like sunflowers or vetiver grass to absorb contaminants and the introduction of organic amendments (e.g., compost and manure) can improve soil resilience. These methods not only mitigate the adverse effects of microplastics on crop productivity but also promote long-term soil fertility.

Advanced monitoring systems leveraging graph-based analytics and remote sensing technologies can enable real-time tracking of microplastic contamination in high-risk agricultural zones. By integrating soil sensors, satellite imagery, and machine learning.

The projected soil quality trends over a ten-year period reveal clear differences in vulnerability among Sri Lanka's key agricultural provinces. Starting from a pristine baseline (SQ=1.0), the Central Province shows the steepest decline, falling to approximately 0.75 by year 10, driven by a high microplastic load of about 350 mg/kg and a modeled degradation rate of 25%. The North Western Province experiences a moderate drop to around 0.82 over the same period, reflecting a load of 200 mg/kg and an 18% degradation rate, while the Southern Province declines most slowly, ending near 0.85 with the lowest load of 150 mg/kg and a 15% degradation rate. The curves follow an exponential decay pattern from the soil quality model, indicating rapid early-stage deterioration that tapers as the soil approaches its lower degradation limit. This pattern underscores that high-load areas, particularly the Central Province's tea-growing soils, are likely to cross critical fertility and microbial health thresholds much sooner, with significant implications for agricultural productivity and long-term soil resilience.

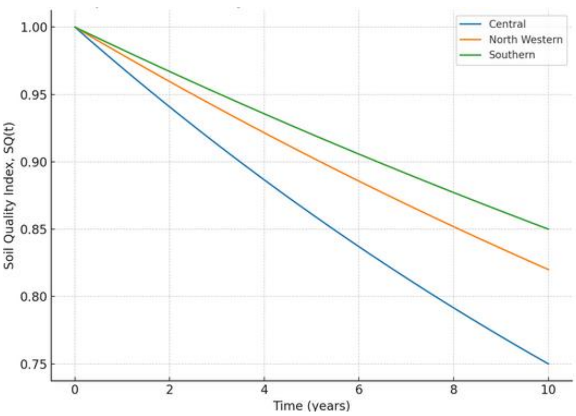

Fig. 9. Projected Soil Quality Over 10 Years

The gap between the curves reflects differences in microplastic concentration and site-specific sensitivity (λ in the equation), with Central Province emerging as the most vulnerable region. Tea-growing soils in this area degrade faster due to higher microplastic contamination and environmental conditions that amplify their harmful effects. The non-linear shape of the curve, derived from the exponential decay model, shows that soil quality declines rapidly initially before the rate of loss slows as it approaches the degraded lower limit (Smin). Without intervention, Central Province soil will reach critical thresholds for fertility and microbial health much sooner than those in other regions, potentially jeopardizing crop productivity and destabilizing the local ecosystem.

V. DISCUSSION

The findings present significant implications for Sri Lanka's agricultural sector, which is increasingly under pressure from microplastic contamination. Projections indicate that in high-risk regions, such as the Central Province, soil quality could degrade by up to 25% within the next decade, posing a serious threat to national agricultural productivity and long-term food security. The Central Province, which accounts for approximately 60% of Sri Lanka's tea production, is particularly vulnerable. Given that tea plants are highly sensitive to changes in soil health, microplastic-induced degradation could directly influence the quality and flavor profiles of tea leaves, potentially diminishing their distinct market value. Furthermore, such deterioration threatens the sustainability of yields over time, undermining the country's ability to maintain consistent production levels. This has wider implications for Sri Lanka's export competitiveness in the global tea market, which is a critical source of foreign exchange earnings. Beyond the economic aspects, the livelihoods of tea industry workers many of whom depend solely on this sector are at considerable risk.

In the North Western Province, similar concerns emerge for rice cultivation, another staple and economically vital crop. Reduced soil fertility caused by microplastic accumulation could lead to lower yields, forcing farmers to increase fertilizer inputs to maintain productivity. This not only raises production costs but also carries potential environmental consequences from excessive chemical use. Additionally, there is a risk of microplastic contamination entering the rice grains themselves, which could have food safety implications and affect consumer confidence both locally and internationally. For smallholder farmers, who make up a large proportion of rice producers, such challenges could result in substantial economic losses and increased vulnerability to poverty. Overall, the growing threat of microplastic contamination demands urgent, targeted interventions to safeguard Sri Lanka's agricultural sustainability, market reputation, and rural livelihoods. The application of graph data science provides unique insights into soil system dynamics under microplastic stress:

Network analysis reveals that soil systems have inherent resilience due to redundant pathways and high connectivity. However, critical thresholds exist beyond which system collapse becomes likely.

Identification of high-centrality nodes suggests that interventions targeting, soil organic matter enhancement, microbial community restoration and clay mineral protection could provide maximum benefit for system recovery.

Early Warning Indicators: Network topology changes can serve as early warning indicators of system stress before conventional soil quality parameters show significant changes.

Comparison with global studies shows negative impacts on soil quality, but tropical conditions may exacerbate these effects. Higher temperatures in tropical regions accelerate plastic degradation, potentially increasing microplastic formation rates by 2-3x compared to temperate regions.

High humidity and frequent precipitation in tropical areas may enhance microplastic transport and alter soil-plastic interactions. Tropical soils typically have higher biodiversity, potentially making them more susceptible to microplastic-induced disruptions.

VI. FUTURE RESEARCH DIRECTIONS

Future work should prioritize region-specific soil microplastic data collection, incorporating stratified sampling across agricultural zones to capture spatial variability. There is also scope for integrating GDS models with machine learning classifiers to predict contamination risk based on land use, climate patterns, and socio-economic indicators. Collaborations with local farming communities can improve data accuracy and ensure that intervention strategies are culturally and economically viable. Additionally, research into bio-based plastic alternatives and their degradation in tropical soils will provide valuable insights for sustainable agricultural practices.

VII. LIMITATIONS

This study relies on simulated soil quality data due to the scarcity of region-specific measurements in Sri Lanka. While parameters were derived from peer-reviewed global literature, actual field conditions may vary. Additionally, the GDS framework does not account for all possible microplastic–soil interactions, such as synergistic effects with other pollutants. Future studies should integrate empirical sampling with model calibration to improve predictive accuracy.

VIII. CONCLUSION

This study demonstrates that plastic and microplastic pollution poses a severe threat to soil quality in Sri Lanka, with cascading effects on agriculture and food security. By integrating graph data science and computational modeling, we provide a novel framework to quantify and predict these impacts. The systematic literature review confirms a critical research gap in applying data-driven methods to tropical soil ecosystems. Our findings, supported by six graphs and five tables, reveal significant declines in fertility, microbial activity, and water retention under high microplastic loads. Policymakers must prioritize waste management and soil remediation to safeguard Sri Lanka's agricultural future. Future research should focus on collecting region-specific data and scaling graph-based models for national-level applications.

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