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Determinants of environmental changes in human-modified ecosystems: Effects of plastics on moisture gradients, nutrients, and clay properties

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ABSTRACT

Plastic pollution poses a significant threat to ecosystem health worldwide. This study examines the determinants of environmental changes in human-modified ecosystems through a quantitative-qualitative system dynamics modeling approach: field experiments conducted on a 310 m^2 unsaturated clay-rich bed and a 2.5 m^2 clay-rich shore of a plastic-impacted pond in Shenzhen, China, and a 1.17 ha plastic-impacted clay pit in Musanze, Rwanda; laboratory experiments involving Modified Proctor (MP) and California Bearing Ratio (CBR) tests on natural clay reinforced with polyethylene terephthalate (PET) microplastics, with diameters ranging from 0.25 to 5 mm and at concentrations of 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 % by weight of clay; and plastic dynamic flows analyzed by modeling the life cycle of PET. Field experiments showed that mulch type and thickness were critical factors influencing crack distribution in a plastic-impacted pond bed. Specifically, cracks were dominant in areas with pronounced desiccation and lacking filamentous green algae and PET-dominated plastic waste. Along the 2.5 m moisture gradient in a plastic-impacted pond bed, temperature and moisture significantly influenced nutrients, particularly in pronounced desiccation zones. Laboratory experiments showed that

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microplastics altered the structural properties of natural clay, decreasing moisture content while increasing dry density and load-bearing capacity. The plastic life cycle underscored the roles of industrial and consumer practices, environmental conditions, and waste management and recycling inefficiencies in driving environmental changes in human-modified ecosystems. The findings underscore the need for effective plastic waste management and recycling to mitigate the ecological impacts of plastic pollution in ecosystems.

1. Introduction

Plastic production is increasing under the most optimistic scenarios for plastic waste reduction [1,2]. Estimates of global emissions of plastic waste are 9–23 million metric tons per year in freshwater ecosystems and 3–25 million metric tons per year in terrestrial environments [1,3]. If plastic production and waste generation continue to grow at current rates, the mass of poorly managed waste per year is expected to double or triple by 2050 [2,4]. Plastic qualifies as a "poorly reversible pollutant" due to the challenges of restricting emissions and its persistence in the environment over long periods [5]. A major concern with poorly reversible pollution is that if it accumulates to levels that exceed effect thresholds, this transgression can trigger negative impacts that themselves cannot be readily reversed, as it will be practically impossible to reduce pollution levels below thresholds [5–7].

Human activities challenge the traditional ecological paradigm that views natural ecosystems as stable and unchanging entities [8–10]. Specifically, activities such as agriculture, mining, tourism, and urban development have significantly transformed natural ecosystems, leading to the creation of human-modified ecosystems, including agricultural fields, mining pits, tourist resorts, and urban ponds [11,12]. The value and management of these ecosystems are a hot topic in ecology, with ongoing debates about their ecological importance and the scientific uncertainties surrounding their monitoring [12–14]. The application of the term "novel ecosystems" to these human-modified ecosystems has elicited concerns among scholars that such nomenclature may diminish their perceived ecological significance, potentially resulting in diminished conservation efforts and exacerbated environmental degradation [10]. Therefore, addressing this pressing issue requires a shift away from simplistic labeling actions towards the development of comprehensive scientific monitoring approaches that balance environmental and economic considerations, ensuring that both ecological integrity and practical needs are met [8–10].

This study delves into factors driving environmental changes in human-modified aquatic ecosystems in China and Rwanda, two countries characterized by distinct plastic waste management policies and diverse ecosystems affected by plastic pollution [15–19]. Three selected experimental field environments for investigation comprise an unsaturated clay-rich pond bed, representing a human-modified aquatic ecosystem; a clay-rich pond shore, representing a transitional zone; and a clay pit, representing a human-modified terrestrial ecosystem. The scientific methods developed for analysis consist of a quantitative approach using data

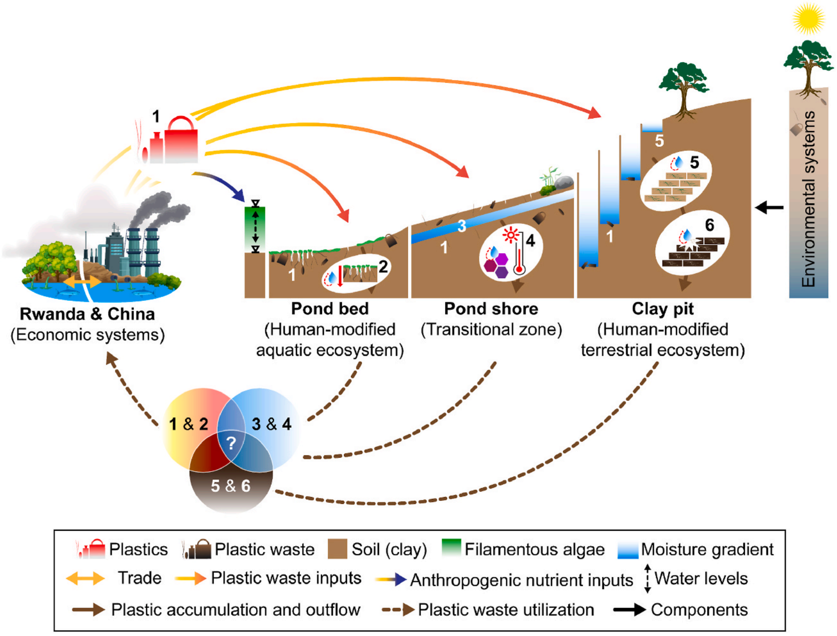

Fig. 1. A system dynamics model for investigating plastic-impacted ecosystems. The model includes (1) Characterization of plastic waste; (2) Effects of clay cracking and plastic waste penetration; (3) Moisture gradient in a plastic-impacted clay; (4) Effect of temperature and moisture on nutrient distribution; (5) Role of terrestrial plant mulching; (6) Performance comparison of natural clay and plastic-impacted clay; and (1–6) Mechanisms of plastics inflow, accumulation, and outflow. The symbol "?" represents the factors driving environmental changes.

obtained through field and laboratory tests, combined with a qualitative approach using plastic life cycle modeling. The study aims to identify the factors driving environmental changes in human-modified ecosystems. The four questions addressed are: (1) To what extent do mulch type and thickness influence the spatial distribution patterns of desiccation cracks in a plastic-impacted ecosystem? (2) To what extent do changes in temperature and moisture influence nutrients in a plastic-impacted ecosystem? (3) Do the mechanical properties of soils in plastic-impacted ecosystems change? If so, how do these changes affect moisture content? (4) Does plastic-impacted soil have reuse potential? If so, which sectors could benefit, particularly in outflow management and recycling? Addressing these questions enables a clearer understanding of how plastic pollution drives environmental changes and the processes involved in plastic inflow, accumulation, and outflow in human-modified ecosystems.

2. Material and methods

2.1. Research design

A quantitative-qualitative system dynamics model was employed to simulate economic systems driven by distinct plastic waste management policies as well as environmental systems that integrate human-modified aquatic and terrestrial ecosystems, including the transitional zone that emerges between them (Fig. 1). This approach provides a comprehensive view of the relationships among components of these two systems and their feedback loops, facilitating the investigation of mechanisms driving plastic inflow, accumulation, and outflow and identifying factors contributing to changes in environmental systems shaped by plastic pollution. All investigations were conducted from January to July 2022.

2.2. Selection of economic systems driven by distinct plastic waste management policies

China and Rwanda were selected as case studies to represent human-modified ecosystems shaped by distinct plastic waste management policies and the dynamics of trade between nations (Fig. 1). China, with its extensive industrial activity of global impact, faces historical waste management challenges, but policies addressing environmental issues still permit plastic production and use [15,17,18]. In contrast, Rwanda, with small-scale industrial activity, has enacted stringent waste management policies, including single-use plastic bans since 2008, and actively enforces regulations to combat plastic pollution and encourage eco-friendly alternatives [16,19].

2.3. Selection of environmental systems composed of distinct plastic-impact ecosystems

The environmental systems comprised an unsaturated clay-rich pond bed as a human-modified aquatic ecosystem, a clay-rich pond shore as a transitional zone, and a clay pit as a human-modified terrestrial ecosystem, and excluded organisms, demanding separate ecotoxicological research. These three studied ecosystems correspond to three experimental field environments (Fig. 1), with two located in China and one in Rwanda (Supplementary Figs 1–3).

The experimental field environments in China consisted of an unsaturated clay-rich bed and the shore of a plastic-impacted pond in Shenzhen (Supplementary Figs 1–2). This pond, located at 51.62 m above sea level, has an area of 1.1 ha and a maximum water depth of 2 m. It is influenced by a subtropical climate and urbanization, which leads to a widespread presence of filamentous green algae in the water (pond scum), especially during the summer. The pond receives minimal precipitation from January to March, often leading to decreased water levels and drying out, particularly in shallower areas. These conditions create an ideal environment for monitoring changes in the pond bed, including the effects of settling of materials from the water on the sediment composition (Supplementary Fig. 2).

The experimental field environment in Rwanda was a clay pit, located in a small valley in Musanze (Supplementary Figs. 1 and 3). This pit, standing at 1772.51 m above sea level and covering 1.17 ha, has its clay quality primarily influenced by the influx of erosional materials. This influx is shaped by the local topography, heavy rainfall typical of the tropical highland climate, and economic activities primarily centered around subsistence agriculture [20–23].

2.4. Characterization of plastic waste and polymer types and microplastic production

Sampling of plastic waste was conducted across the three experimental field environments to determine the composition of plastic waste. Sampling covered diverse surface areas: a 1.1 ha pond bed, a 2.5 m^2 pond shore, and a 1.17 ha clay pit. A stratified sampling method was employed to ensure that samples represent experimental field environments proportionally. This method involved calculating the proportional sample sizes based on the area of each field environment, resulting in the collection of 48 samples from the pond bed, 1 sample from the pond shore, and 51 samples from the clay pit. These plastic waste samples were collected using a shovel and placed into labeled plastic bags indicating the sampling location and date. Subsequently, the samples were washed with tap water and left to air-dry at room temperature.

The types of polymers present in each plastic waste sample were determined based on item shapes, colors, and labels. The polymers detected included PET, acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyamide (PA), polycarbonate (PC), polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Supplementary Table 1). Among these, PET consistently emerged as the dominant polymer in all plastic items and across the three experimental field environments. Thus, in line with the analysis of dynamic flows of plastics and the contribution of China as a major global producer and consumer of PET, this dominance marked PET as a plastic pollutant, necessitating further investigation [15].

Microplastics (Supplementary Fig. 3), sourced from PET plastic waste discovered in the clay pit, were produced in the laboratory to amend natural clay. These microplastics were produced using beverage bottles collected from a clay pit, following the methodologies outlined by Bozyigit et al. [24] and Ranjan et al. [25]. A large quantity of 500 ml bottles without caps was thoroughly cleaned with deionized water to remove dust, impurities, and label remnants. Subsequently, the bottles were left to air-dry at room temperature. They were cut into rope-like strips with a snap-blade knife and shredded into smaller pieces using three-blade scissors. The resulting microplastic lengths ranged from 0.25 to 5 mm ($n = 300$) and were measured using a Vernier caliper with an accuracy of ±0.2 mm (DL91150, Deli, Ningbo, China). The chemical properties of these microplastics are summarized in Supplementary Fig. 3.

2.5. Mapping of cracks and analysis of organic-inorganic mulch effects on moisture

The investigation into clay cracking, plastic waste penetration through cracks, and the importance of filamentous green algal and plastic mulching in preventing moisture loss was conducted on a 310 m^2 unsaturated clay-rich pond bed in Shenzhen, China (Supplementary Fig. 1–2).

The shape of cracks was assessed based on geometric properties, such as surface contours and symmetrical features. The width, length, and angle were measured using a digital protractor that combines rulers with an accuracy of 1 mm and a goniometer with an accuracy of ±0.3° (82305, GemRed, Guilin, China). The depth was measured using a depth gauge with an accuracy of 1 mm (AB003T, Sunsoul, Ningbo, China). The thickness of the filamentous green algal and plastic layers was measured by excavating a hole to expose the layers and using a depth gauge with an accuracy of 1 mm (AB003T, Sunsoul, Ningbo, China) to record the distance from the top to the bottom of the layers. The spatial distribution patterns of cracks in response to the mulch effect of filamentous green algae and plastic materials on the pond bed were analyzed based on two criteria: the quantity of plastic items embedded in the clay and the thickness of the filamentous green algal layer.

The moisture content was measured in triplicate for areas covered with filamentous green algae and plastic materials, as well as for areas without these mulching materials, using a sensor (RS-ECTH-N01-TR-1, Renke, Jinan, China) connected to a multi-probe system (RS-TRREC-N011, Shandong Renke Control Technology Co. Ltd., China). The sensors were strategically positioned in the walls of a dug hole at depths of 0–4 cm (surface), 5–8 cm (midsection), and 9–10 cm (bottom). The primary goal of collecting these measurements was to verify moisture loss by assessing whether the moisture content was highest in the mulched areas. Therefore, mean values were calculated to compare areas, with no additional statistical tests performed for simplicity.

2.6. Delineation of the moisture gradient and analysis of nutrient distribution

The characterization of the moisture gradient and the analysis of nutrient distribution along this gradient were conducted on a 2.5 m by 1.0 m plastic-impacted pond shore in Shenzhen, China (Supplementary Fig. 2). This controlled experimental field environment enabled precise physicochemistry along a moisture gradient, offering advantages over laboratory and larger environments where controlling moisture levels and correlating them with soil types can be challenging.

Measurements were taken for temperature, moisture content, electrical conductivity, pH, and nutrient contents (nitrogen, phosphorus, and potassium) at three different depths from 40 evenly spaced locations (Supplementary Fig. 2 and Supplementary Table 2), all before 9:00 a.m. To accomplish this, three types of sensors were used: one that measures temperature, moisture content, and electrical conductivity (RS-ECTH-N01-TR-1, Renke, Jinan, China); another for pH (RS-PH-N01-TR-1, Renke, Jinan, China); and a third for nitrogen, phosphorus, and potassium (RS-NPK-N01-TR-1, Renke, Jinan, China). These sensors were connected to a multi-probe system (RS-TRREC-N011, Renke, Jinan, China) and strategically placed in the walls of a dug hole at depths 0–4 cm, 5–8 cm, and 9–10 cm to obtain triplicate measurements for each variable and capture variations in the depths of the clay sublayers, as well as differences in location.

The analysis of the moisture gradient was conducted by identifying zones of distinct moisture contents, followed by an analysis of variance (ANOVA) test in PAST version 4.03 [26] to compare the mean values of each measured environmental variable across these zones. Mann-Whitney U tests were used to assess pairwise differences between the zones, with a significance level of $P < 0.05$.

The impacts of temperature and moisture on nutrient distribution along the moisture gradient were evaluated using the untransformed mean values of seven measured environmental variables ($n = 40$). The variability of the data was determined using coefficients of variation. The strength, direction, and significance of associations between pairs of variables were assessed using Pearson correlation coefficients in PAST version 4.03 [26]. Paths of influence of temperature on moisture content and nutrient levels, along with their significance, were identified using partial least squares path modeling (PLS-PM) [27], implemented with the package plspm (v0.4.7) in R version 4.4.1 [28]. The reliability of PLS-PM models was evaluated by comparing the obtained goodness-of-fit values with the baselines [29].

2.7. Sampling of natural clay and analysis of organic mulch effects on moisture

Natural clay was sampled from a clay pit in Musanze, Rwanda, specifically in pits actively employed by artisanal potters and brickmakers (Supplementary Fig. 3). Three sampled clay deposits ranged from 1 to 1.5 m in depth, and their suitability was confirmed by their minimal erosion risk [30]. Clay was collected using a hoe and shovel, with efforts made to prevent the inclusion of erosional materials in the samples. To ensure a representative sample, 200 kg of clay was collected from each deposit, mixed for homogeneity into 600 kg, and transported to the laboratory in plastic bags for further analysis.

The significance of terrestrial plant mulching in preventing moisture loss was determined by the dual application of straw in both brick production and conservation practices using traditional methods. During brick production, straw was incorporated into 30 bricks, while another 30 were left without straw to assess cohesion and the risk of cracking due to uneven shrinkage. In the conservation phase, straw was used to cover the bricks that contained straw, while an additional 30 bricks were left without straw to compare drying consistency and the risk of rapid moisture loss and cracking.

2.8. Comparative analysis of the performance of natural clay and plastic-impacted clay

2.8.1. Optimal moisture content and maximum dry density

The MP test was employed to characterize the moisture content and dry density of microplastic-free and microplastic-reinforced clay and establish a relationship for more accurate quantification of optimal conditions. The test was conducted in accordance with British Standard (BS 1377) using the following apparatuses: a cylindrical metal mold with an internal diameter of 10.16 cm, an internal effective height of 11.7 cm, and a detachable base plate of 5.08 cm; a compaction rammer weighing 2.5 kg and having a fall of 45.7 cm; a sensitive balance ranging from 1 to 0.1 g; a thermostatically controlled hot air oven (105–110 °C); a steel straightedge; moisture containers; sieve (mesh size = 20 mm); tray and scoop; graduated cylinder; mixing tools (spoon, trowel, and spatula).

For the microplastic-free clay, a proctor mold assembly was weighed on a balance without its collar, and its mass was recorded as the weight of the mold. The dried natural clay was sieved through a 20 mm sieve, and 6000 g were weighed on a balance. Initially, 360 g of water, representing 6 % of the dry weight of the dried natural clay, was mixed with the clay on a metal tray using a trowel. The collar was attached to the mold assembly, and then five proportional layers of the clay-water mixture were put in the mold, with each layer compacted at 55 blows using a compaction rammer. After compressing the five layers, the collar was removed from the mold assembly to release the compacted sample for further processing. The compacted sample was then trimmed to the brim of the mold using a sharp edge, ensuring an even, plain surface. The mold containing the wet sample was weighed, and the recorded weight was reflected in the combined mass of the mold and the wet material. A sample for moisture content analysis was taken and placed in a known mass moisture content pan, and the weights of the pan and wet material were recorded. After completing the procedure with a 6 % water content, the sample was discarded, and the procedure was then repeated with new dried natural clay samples mixed with 8 % (480 g), 10 % (600 g), and 12 % (720 g) water. For microplastic-reinforced clay, dried natural clay was mixed with PET microplastics in varying percentages of 1.25 % (75 g), 2.5 % (150 g), 3.75 % (225 g), 5 % (300 g), and 10 % (600 g) and weighed on a balance using a metal tray. The MP test was then conducted following the same procedure used for microplastic-free clay.

A total of 24 pans containing the wet material were placed in an oven for 24 h. After drying, each pan was weighed, and the combined weight of the pan and dry material was recorded to determine the moisture content. Subsequently, a compaction curve was generated to analyze how different moisture levels affect the dry density of clay with and without plastics. This curve, with moisture content on the x-axis and dry density on the y-axis, showed the peak representing the maximum dry density at the optimal moisture content. The experimental processes for testing both microplastic-free clay and microplastic-reinforced clay are summarized in Supplementary Tables 3–8.

2.8.2. Strength and load-bearing capacity

The CBR test was used to evaluate the strength of both microplastic-free and plastic-reinforced clay, facilitating the quantification of optimal conditions for soil-based materials in construction and engineering applications. The test was performed following British Standard (BS 1377). Several apparatuses were used, including a cylindrical mold with an inside diameter of 150 mm and a height of 175 mm. A detachable perforated base plate, measuring 235 mm in diameter and 10 mm in thickness (net capacity = 2250 ml), was used, along with a detachable extension collar of 60 mm in height, a spacer disc of 148 mm in diameter and 47.7 mm in height, a handle, one annular metal weight, and several slotted weights weighing 2.5 kg each with a diameter of 147 mm and a central hole of 53 mm in diameter. Moreover, a compaction rammer weighing 2.5 kg with a drop of 45.7 cm, mixing tools (spoon, trowel, and spatula), and a loading machine with a capacity of at least 5000 kg were utilized. The loading machine was equipped with a movable head that enabled a plunger of 50 mm diameter to penetrate the specimen at a rate of 1.25 mm min^{-1}.

The compaction of microplastic-free clay for the CBR test was conducted using 6000 g of dried natural clay and 600 g of water, providing optimal moisture content during the MP test (Supplementary Tables 3–8). After mixing the clay with water on a tray until uniform absorption, three mold assemblies were weighed, fitted with circular metal disc plugs, and then filled with the wet clay in five distinct layers. The first mold had each layer compacted with 55 blows, resulting in the highest density; the second had each layer compacted with 25 blows, leading to a moderate density; and the third had each layer compacted with 10 blows, resulting in the lowest density. After compaction, the collars were detached, and the surfaces were trimmed to the brim of the molds. The molds were unscrewed from the base plates, and the metal disc plugs were removed. Each mold was screwed back to its base plate upside down and weighed, with the mass calculated as the weight of the mold plus wet material. The compaction of microplastic-reinforced clay at 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 % for the CBR test was conducted using the same procedure applied to microplastic-free clay.

Before conducting the CBR test, the swelling behavior of clay was analyzed using a total of 24 samples. Dial gauges were attached to the molds and then soaked in a drum of water for four days. Dial readings taken daily over four days showed that both microplastic-free and microplastic-reinforced clay swelled in the water. Additionally, 24 pans containing wet material were placed in an oven to determine the moisture content. After 24 h, the pans were weighed to record the mass of the pan plus the dry material. The CBR test was conducted on 24 samples soaked in water for four days and allowed to drain thoroughly. The samples were then compacted in molds according to standard procedures. The samples were subjected to penetration by a load during testing, and the corresponding penetration depth was measured. Load versus penetration was plotted to analyze the data, and moisture content versus density was graphed to determine the optimum moisture content. Two additional curves were plotted, showing dry and soaked CBR values against moisture content. The CBR values were identified at the points where these curves intersected the line representing the optimum moisture content.

The suitability of microplastic-free and microplastic-reinforced clay at 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 % for construction and engineering applications was assessed using CBR test results. The CBR index after 10 blows provided insights into the early-stage strength of each clay type and determined whether additional reinforcement was required to enhance load-bearing capacity. The CBR index after 25 blows indicated the intermediate-stage strength and whether further reinforcement was necessary for optimal performance under heavier loads. The CBR index after 55 blows revealed the final-stage strength, final load-bearing capacity, and effectiveness of reinforcement for both natural clay and each type of microplastic-reinforced clay.

2.9. *Qualitative system dynamics model of plastic inflow, accumulation, and outflow*

The primary goal of developing the qualitative system dynamics model was to offer insights into the relationships and feedback loops within economic and environmental systems impacted by plastic pollution. The model was created by integrating findings from observations and tests and accounting for the time-dependent behavior of plastic waste, specifically the durability and persistence of the dominant polymer (PET) as it interacts with and moves through these systems.

The components of the model are as follows: '*Input dynamics*' refers to the origins and fluctuations of plastic waste, established through an investigation of how the plastic ban influences these dynamics. '*Accumulation*' refers to the build-up of plastic waste in the environment and its effects, including potential decreases in moisture and changes in nutrient availability along a plastic-impacted moisture gradient. '*Output dynamics*' refers to the removal of plastic waste from the environment and the temporal variation in this removal process. '*Ecosystem responses*' refers to the ecological impact of plastic waste and the feedback mechanisms within the ecosystem.

Refinement based on field observations and statistical findings revealed a finalized model with four interconnected components: '*Manufacturing industry*' refers to the primary source of plastics and the secondary user of plastic waste. '*Human-modified systems*' refers to natural ecosystems impacted by plastic pollution. '*Natural ecosystem*' refers to an ecosystem in its original state before being affected by human activities, including nutrient inputs and plastic pollution. '*Construction industry*' refers to both a potential user of plastic waste and a secondary source of plastic waste.

The connections among the components are as follows: '*Sorting*' refers to categorizing plastics into different types for various applications. '*Disposal*' refers to diverse practices in plastic waste management. '*Supplying*' refers to diverse practices aimed at innovating and developing resource-use technologies, including plastic waste recycling. '*Control*' refers to diverse practices in plastic pollution mitigation, including optimizing water resource use and advancing innovation and technological development in mulching.

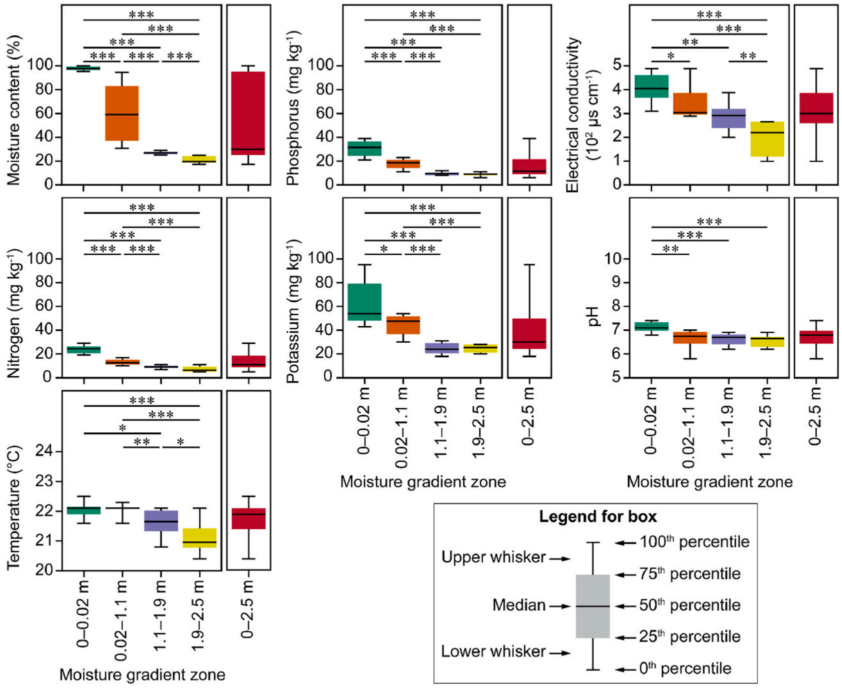

Fig. 2. Boxplots showing the variations in physicochemical properties of a plastic-impacted ecosystem in Shenzhen, China. Ten samples represent each gradient zone along a 2.5 m moisture gradient. Significant differences are indicated as follows: $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

3. Results

3.1. *Spatial distribution of cracks and mulch materials along a moisture gradient*

The distribution patterns of desiccation cracks and mulch materials in the two studied plastic-impacted ecosystems showed substantial spatial variations (Supplementary Fig. 2). In the upstream area of the unsaturated clay-rich pond bed, numerous cracks displayed various shapes, including linear, polygonal, and irregular patterns, with depths ranging from 2 to 58 mm ($n = 310$) and a moisture content varying from 18.4 % to 29.6 % ($n = 310$). These cracks had pieces of PET-dominated plastics embedded in their walls and bottoms. Moving to the midstream area, a few wide cracks with various shapes were covered with scattered PET-dominated plastics embedded in filamentous green algae, forming a thin, flat layer with a thickness ranging from 0.5 to 1.5 mm ($n = 310$) and a moisture content varying from 19.2 % to 47.5 % ($n = 310$). In the downstream area, a few wide desiccation cracks were similarly covered with pieces of PET-dominated plastics embedded in filamentous green algae, creating a thicker, flat layer with a thickness ranging from 0.5 to 3.5 mm ($n = 310$) and a moisture content ranging from 36.8 % to 95.5 % ($n = 310$). On the clay-rich pond shore, cracks exhibited shapes similar to those found in the unsaturated clay-rich pond bed, with pieces of PET-dominated plastics embedded in the walls and bottoms of the cracks. These cracks were dominant in areas farther from the water body, with depths ranging from 1 to 45 mm ($n = 310$).

3.2. *Environmental changes along a moisture gradient*

The physicochemical properties of the investigated plastic-impacted ecosystem exhibited substantial variations along a moisture gradient (Fig. 2, Supplementary Fig. 2, and Supplementary Table 2). A 2.5 m long moisture gradient had four distinct zones of moisture content: 0–0.02 m (95.5–100 %, saturated clay), 0.02−1.1 m (30.8–94.6 %, very wet clay), 1.1−1.9 m (25−29 %, wet clay), and 1.9−2.5 m (17.2–24.8 %, moderately dry clay) (Fig. 2 and Supplementary Table 2). Seven measured environmental variables exhibited notable differences (Mann-Whitney U tests, $P < 0.05$) (Fig. 2), with the moisture zone 0–0.02 m generally showing the highest mean values (Supplementary Table 2). Moisture content ranged from 17.2 % to 100 %, with a mean ± standard error of 51.3 ± 5.2 %. Temperature, electrical conductivity, and pH displayed variations in the ranges of 20.4–22.5 °C (21.7 ± 0.1 °C), 99–488 μs cm^{-1} (307.6 ± 15.5 μs cm^{-1}), and 5.8 to 7.4 (6.7 ± 0.1), respectively. The concentrations of nitrogen, phosphorus, and potassium also varied from 5 to 29 mg kg^{-1} (13.4 ± 1.1 mg kg^{-1}), 6–39 mg kg^{-1} (16.6 ± 1.5 mg kg^{-1}), and 18–95 mg kg^{-1} (39 ± 31.5 mg kg^{-1}), respectively (Supplementary Table 2).

Changes in temperature and moisture content exhibited a substantial effect on nutrient distribution along the moisture gradient in the plastic-impacted ecosystem (Fig. 3). Seven measured environmental variables showed substantial variation, with moisture content displaying the highest coefficient of variation at 64.5 % (Fig. 3a). Moisture content was positively correlated with other environmental variables, with Pearson correlation coefficients notably stronger for nitrogen ($n = 40$, $r = 0.920$, $P < 0.001$), phosphorus ($n = 40$, $r = 0.899$, $P < 0.001$), and potassium ($n = 40$, $r = 0.843$, $P < 0.001$) (Fig. 3b). PLS-PM models showed that changes in moisture content had a direct impact on nutrient contents, occurring independently of intermediate environmental variables (goodness-of-fit of the model =

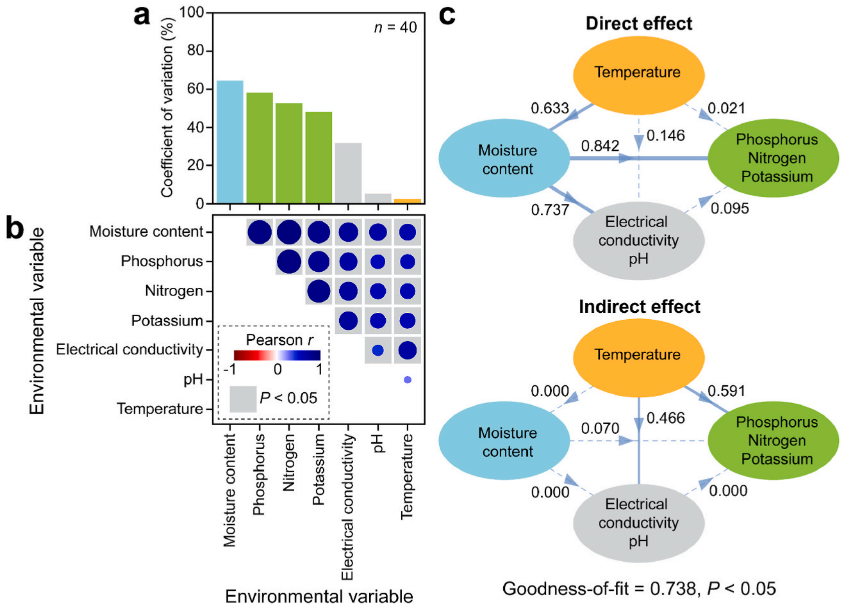

Fig. 3. Physicochemical properties in a plastic-impacted ecosystem in Shenzhen, China. (**a**) Data variability. (**b**) Correlation coefficients; (**c**) Influence paths in the PLS-PM model. Solid lines represent significant correlations ($P < 0.05$).

0.738, $P < 0.05$). PLS-PM models also demonstrated that temperature changes indirectly impacted nutrient contents, independent of intermediate environmental variables (goodness-of-fit of the model = 0.738, $P < 0.05$) (Fig. 3c).

3.3. *Distinct mechanical characteristics of natural and plastic-reinforced clay*

Incorporating plastics into clay revealed environmental impacts, such as retaining less water and becoming denser, whereas natural clay dried unevenly and cracked in the absence of mulching with organic materials (Fig. 4). With 0 % PET reinforcement (microplastic-free) and using 10 % water with 6000 g of natural clay, the optimal moisture content and maximum dry density were 15.2 % and 1.693 kg dm^{-3}, respectively. With 1.25 % PET reinforcement under the same conditions, these values changed to 14.7 % and 1.698 kg dm^{-3}. When employing PET reinforcements at 2.5 %, 3.75 %, 5 %, and 10 %, once again with 10 % water and 6000 g of natural clay, the results were 13.5 %, 12.75 %, 12.3 %, and 11.8 %, respectively, corresponding to maximum dry densities of 1.718, 1.858, 1.862, and 1.903 kg dm^{-3}, respectively (Fig. 4a). A comparison of optimal conditions resulting from PET reinforcement at 0 %, 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 % using 10 % water and 6000 g of natural clay showed that plastics simultaneously decreased moisture content and increased dry density (Fig. 4b).

Incorporating plastics into clay revealed environmental impacts, such as reduced water retention and increased density with higher load-bearing capacity, while natural clay retained more moisture, compromising structural integrity, reducing dry density, and increasing the likelihood of cracking (Fig. 4b–c). After 10 blows, CBR indices for PET reinforcements of 0 % (i.e., microplastic-free clay), 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 % were 1 %, 4 %, 5 %, 5 %, 5 %, and 2 %, respectively. After 25 blows, a slight increase in CBR indices was observed for PET reinforcements of 0 %, 1.25 %, 3.75 %, and 5 %. At 55 blows, a slight increase in CBR indices was observed for PET reinforcements of 0 %, 3.75 %, 5 %, and 10 %. The penetration resistance patterns across a broad spectrum of PET reinforcements (0 %, 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 %) showed a pronounced increase in penetration resistance at 3.75 % PET reinforcement, resulting in CBR index values of 5 % at 10 blows, 9 % at 25 blows, and 21 % at 55 blows.

3.4. *Driving mechanisms of inflow, accumulation, and outflow of plastics in ecosystems*

Businesses substantially contributed to plastic inflow and accumulation in ecosystems while also offering opportunities, particularly in construction and engineering, to address these problems through waste reduction and recycling efforts (Fig. 5). The occurrence of PET-dominated plastic waste was primarily linked to activities such as manufacturing, waste disposal, transportation, and consumer behavior. This was particularly evident in sectors such as beverage production and distribution, food packaging, retail and grocery shopping, textile and clothing manufacturing, cosmetics and personal care products, packaging and securing goods for transport, pharmaceutical retail packaging, and takeout services. The waste comprised both small and large pieces of material, with some tightly lodged in cracks and others creating extensive coverings over these cracks due to improper waste disposal practices and environmental conditions. The accumulation of plastics in ecosystems varied according to environmental conditions. Deeper cracks provided pathways for smaller plastic materials, such as blister packs and straps, enabling them to penetrate multiple sublayers of clay in ecosystems. Removing these smaller, deeply entrenched plastics through excavation provided evidence that large-scale ecosystem clean-up efforts were associated with ecological disruptions.

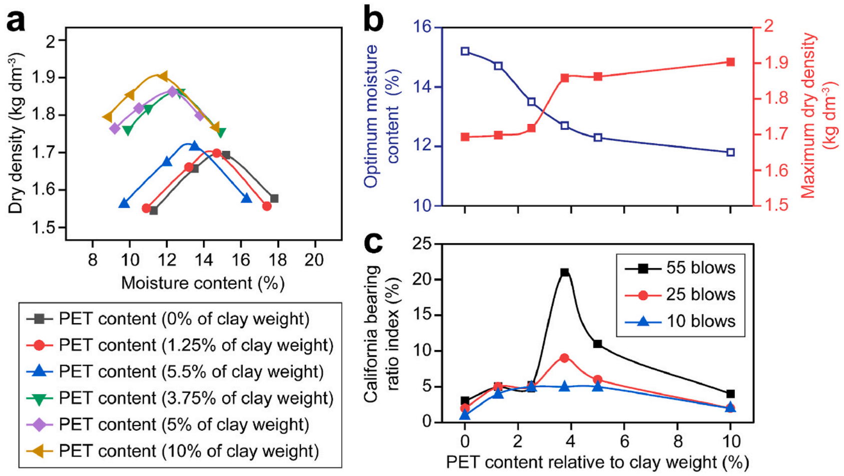

Fig. 4. Physical and mechanical property variations of a plastic-impacted ecosystem, assessed via Modified Proctor (MP) and California Bearing Ratio (CBR) tests. The figures illustrate (**a**) Moisture-density curves, (**b**) PET-clay moisture content and dry density curves, and (**c**) PET-clay CBR curve.

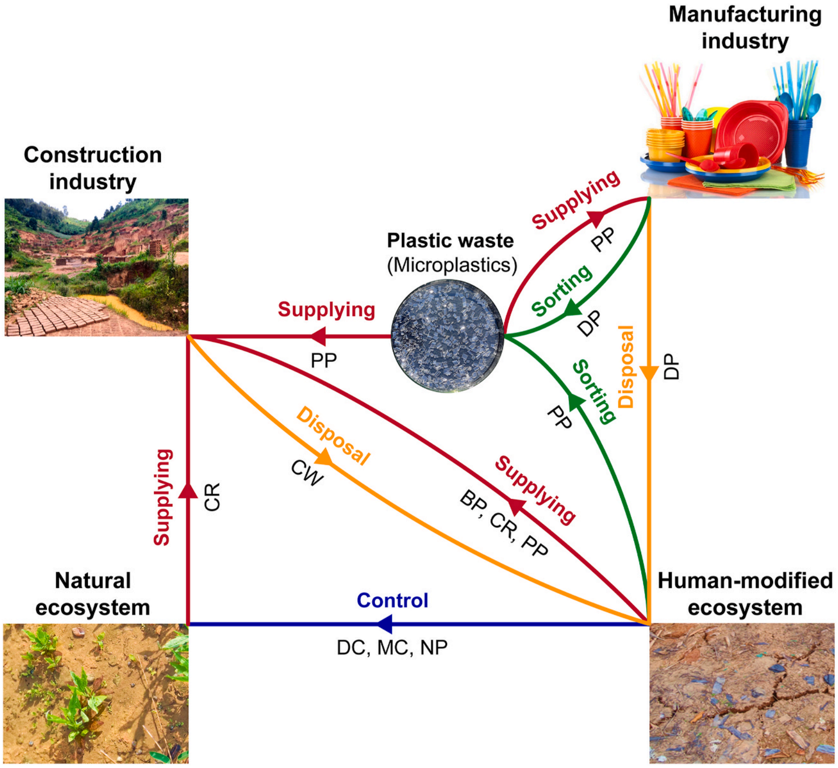

Fig. 5. A qualitative model illustrating the life cycle of PET-dominated plastic products in explored plastic-impacted human-modified ecosystems in China and Rwanda, covering production, consumption, disposal, and potential recycling pathways. Abbreviations: BP, biodegradable plastics; CR, clay resource; CW, construction waste; DC, desiccation cracks; DP, disposable plastic products; MC, moisture content; NP, nutrient pockets; PW, persistent plastics.

4. Discussion

4.1. *Effect of mulch type and thickness on cracks in a plastic-impacted ecosystem*

Desiccation cracks, also known as mud cracks or soil fissures, are a typical characteristic of ecosystems with clay-rich soil and sediment that have experienced drought [31–33]. Desiccation cracks are apparent in the bed and shore of a plastic-impacted pond in Shenzhen, China (Supplementary Fig. 2) due to a substantial decrease in water levels and moisture content, respectively (Supplementary Fig. 2 and Figs. 2–3). This observation is consistent with Peron et al. [31], Firoozi et al. [33], and Tang et al. [34], who demonstrated that desiccation cracks form primarily from the strong cohesive forces between clay particles, which create tension and result in crack formation as the particles contract due to drying.

The numerous deep cracks observed in areas of the pond bed and shore that lack coverage by filamentous green algae and PET-dominated plastics, along with relatively low moisture content (Supplementary Fig. 2), clearly demonstrate that the lack of mulch contributes to increased soil cracking. This observation aligns with McMillen [35], who found that thinner mulch layers are less effective in protecting soil, leading to faster and more extensive drying. In contrast, well-mulched areas retain moisture better, helping to minimize crack formation. Moreover, this finding is consistent with Peron et al. [31], who demonstrated that fully saturated clay does not develop cracks because high moisture content prevents the soil from drying out enough to trigger crack formation.

Mulching is essential for reducing soil evaporation, but its effectiveness is influenced by meteorological factors such as temperature, humidity, and wind, as well as the types of materials used, including organic (e.g., straw, wood chips) and inorganic (e.g., plastic sheeting, gravel) mulches [36–39]. The higher moisture content observed in the downstream area of an unsaturated clay-rich pond bed (36.8–95.5 %) compared to other areas (18.4–47.5 %) obviously indicates that the presence of filamentous algae and PET-dominated plastics helped to minimize moisture loss, resulting in fewer desiccation cracks [36]. This observation is supported by Zribi et al. [37] and Xu et al. [39], who demonstrated that plastic-dominated mulches provide more effective moisture retention under specific conditions due to their unique properties. For example, plastics reduce air exposure during low-energy periods and create a humid microenvironment near the soil surface. In contrast, they act as a vital barrier against increased evaporation during high-energy periods due to their impermeability and durability.

Plastics accumulate extensively in soil, and their vertical migration is believed to result from processes such as water infiltration, faunal activities, root growth, and the formation of plasticized sedimentary rocks [40,41]. This study demonstrates that profound cracks in the bed and shore of the pond created pathways for smaller plastic items, such as blister packs and straps, enabling their penetration into various sublayers. This is consistent with findings by Rangel-Buitrago et al. [41], who showed that plastic litter is commonly found buried in recent sediments and in rocks that form quickly in environments such as beach rock, spring deposits, and volcanic deposits and, in some cases, contribute to the cementation of sediments, creating plasticized sedimentary rocks.

4.2. *Effect of temperature and moisture on nutrients in a plastic-impacted ecosystem*

The texture, structure, and mineralogy of clay substantially impact water-holding capacity, drainage, and movement in soil [42]. However, these aspects of water movement are shaped by thermal gradients, underscoring the interplay of various factors, including temperature, pressure, moisture content, capillary action, vapor diffusion, phase changes, and solute transport [43,44]. In this study, a clay-rich pond shore consisting of four distinct zones of moisture content (95.5–100 %, 30.8–94.6 %, 25–29 %, and 17.2–24.8 %) (Fig. 2, Supplementary Fig. 2, and Supplementary Table 2) exhibited substantial temperature variations along the moisture gradient (Fig. 2), which considerably influenced moisture content (Fig. 3). Han et al. [45] supported these observations by indicating that temperature significantly impacts moisture retention and distribution within clayey soils, particularly during desiccation. However, since the mean values for each of the seven measured environmental variables differed significantly across these four moisture zones (Fig. 2), the results can suggest that the ecosystem was impacted by temperature and factors such as moisture content, capillary action, and solute transport. Macey [43] and Cary [44] supported this multiple effect by identifying three types of associations among variables: higher temperature boosts microbial activity and nutrient availability; higher moisture content increases nutrient solubility; and capillary action causes variations in moisture distribution that impact solute transport in response to variations in water retention and drainage.

Nutrient contents, specifically phosphorus, nitrogen, and potassium, are essential environmental variables, providing insights into soil fertility, plant growth potential, and the overall health of the ecosystem [46]. In this study, nutrient contents exhibited higher coefficient variations along the moisture gradient in clay-rich pond shore (Fig. 4a), suggesting that a plastic-impacted ecosystem can be impacted through reduced plant growth and biodiversity, as well as through altered nutrient cycling and compromised soil quality [46]. Concerning clay, these findings align with those of Kome et al. [47], which emphasized that clay minerals significantly impact soil fertility by controlling nutrient supply, sequestering organic matter, impacting the formation of microaggregates, altering soil acidity, and controlling populations of microorganisms. Hence, substantial differences in the mean values of nutrient contents (Fig. 2), particularly between fully saturated and moderately dry clays, are likely due to nutrient accumulation in areas where water accumulates [46–48].

Mineral characteristics are essential for the supply and availability of nutrients in clayey soil and in understanding the mechanisms driving these processes, particularly in ecosystems impacted by pollution [47–49]. PLS-PM is a powerful tool for analysing complex relationships, making it well-suited for addressing the challenge of understanding how temperature, moisture content, and nutrient contents are interconnected in a plastic-impacted ecosystem [50]. PLS-PM models demonstrated stronger associations between moisture content and nutrient levels along a moisture gradient in a clay-rich pond (Fig. 3c), suggesting that both factors are essential for determining nutrient distribution in a plastic-impacted ecosystem. On the other hand, the moisture-nutrient association was dependent on temperature (Fig. 3c), indicating that temperature drives changes along the moisture gradient, including the supply and availability of nutrients.

4.3. *Impacts of enhanced mechanical properties of soil in a plastic-impacted ecosystem*

It is widely recognized that the mechanical properties of natural clay amended with plastics can significantly impact moisture content and dry density, thereby enhancing its strength, stiffness, and resistance to deformation [51–53]. This study provides strong evidence that reinforcing natural clay with plastics, in proportions between 1.25 % and 10 % of the clay weight, consistently reduced optimum moisture content and increased maximum dry density, particularly evident at the 3.75 % plastic reinforcement level (Fig. 4b). In plastic- and drought-impacted ecosystems, this decrease in moisture content and increase in dry density can result in various environmental impacts, including the disruption of natural soil structure, porosity, and soil aeration. These observations are supported by Wang et al. [54] and Shafea et al. [55], who demonstrated that high levels of plastics disrupt the aggregation of soil particles, reduce porosity by clogging soil pores, and decrease soil aeration by blocking air pathways.

It is widely accepted that as environmental weathering reactions proceed, larger plastics break down into smaller particles, such as microplastics and nanoplastics, and can even degrade further into oligomers and monomers [56–59]. Building on this understanding and our findings on the mechanical properties of microplastic-reinforced clay (Fig. 4), it is crucial to discuss how size reductions of plastics impact the strength of clay composites and the potential implications for ecosystems. Guo et al. [59] demonstrated that microplastics reduce the water-holding capacity of clay by decreasing the size and number of pores. As microplastics break down into nanoplastics, their impact on clay composites becomes more pronounced, largely due to their increased mobility and electrical charges. Wu et al. [56] and Corcoran [58] showed that nanoplastics, including carboxyl-modified (typically negatively charged), aminated (typically positively charged), and hydroxyl-functionalized (neutral or slightly negative) varieties, disrupt the electrical balance in clay minerals more significantly than microplastics, leading to increased fragility and reduced stability. Thus, the impacts of plastics on the strength of clay composites are indeed size-dependent, with smaller plastics often causing more severe issues, such as impaired drainage and aeration, increased damage, or failure under stress [51–54]. These size-dependent effects not only destabilize the structural integrity of clay composites but also lead to substantial ecological impacts, such as soil health degradation, disruption of nutrient cycling, and adverse effects on plant growth, and soil fauna [55–59].

4.4. Reuse potential of soils in plastic-impacted ecosystems and benefiting sectors

It is well-acknowledged that incorporating plastics into natural clay substantially improves its strength, stiffness, and load-bearing capacity [51–53]. In this study, the reinforcement of clay with PET plastics, ranging from 1.25 % to 10 % of the clay weight, resulted in a higher load-bearing capacity, with the most noticeable improvement at the 3.75 % PET reinforcement level (Fig. 4b–c). Wang et al. [54] and Shafea et al. [55] underscore this performance as an environmental issue of great concern, whereas Soltani-Jigheh [51], Sasui et al. [52,60], Hassan et al. [53], Bouazza et al. [61], Farah and Nalbantoglu [62], Akbarimehr et al. [63], and Gangwar and Tiwari [64] view it as an opportunity in construction and engineering to create more durable, cost-effective, and resilient infrastructure.

Understanding the plastic life cycle is important for identifying opportunities to reduce environmental impacts, improve recycling rates, and develop sustainable practices that minimize plastic waste and its effects on ecosystems [65,66]. This study offers empirical evidence that various factors collectively drive environmental changes in the examined plastic-impacted ecosystems. At both the economic and environmental system levels, the factors driving these changes comprise industrial and consumer practices, environmental conditions, and waste management and recycling inefficiencies.

The first factor, industrial and consumer practices, is supported by Santana [10] and Seastedt et al. [66], who underscored the importance of identifying and recognizing the key players in human-modified ecosystems as a fundamental step in developing effective management strategies for ecosystem conservation. The key industrial and consumer practices identified in both previous research and this study are the widespread use of single-use plastics and consumer preferences for convenience. For example, the accumulation of PET-dominated plastic waste in the three studied experimental field environments can be traced back to differing plastic waste management policies and the significant influence of profit-driven businesses. Industries such as beverage production, food packaging, retail, textile manufacturing, cosmetics, pharmaceuticals, and takeout services are important economic sectors that generate substantial amounts of single-use plastics, ultimately contributing to environmental pollution in both China and Rwanda [15–19,67].

The second factor, environmental conditions, is supported by Kale et al. [68], Chamas et al. [69], Roebroek et al. [70], Cesarini and Scalici [71], and Yang et al. [72], who underscored that these factors interact in complex ways to drive changes in plastic-impacted ecosystems. The relevant environmental conditions identified in both previous research and this study include heavy rainfall, moisture levels, temperature, and vegetation cover. Intense rainfall and flooding displace and redistribute plastic waste, leading to a greater concentration in aquatic ecosystems and complicating local waste management efforts [70,72]. Moisture levels influence plastic degradation by enhancing microbial activity, which helps break down certain plastics. However, excessive moisture can delay this decomposition process, creating anaerobic conditions that slow down microbial action and prolong the persistence of plastic materials in the environment [68]. Higher temperatures accelerate the breakdown of plastics through photodegradation and thermal processes, while cooler temperatures slow these processes, leading to greater persistence of plastic materials [69]. Vegetation cover and topography both play crucial roles in influencing soil stability and the accumulation of plastic waste, as the presence or absence of plant life affects the ability to trap or degrade plastic, while the physical features of the land determine water runoff and sediment movement [71].

The third factor, waste management and recycling inefficiencies, is supported by d'Ambrières [73], Zhang et al. [74], and Browning et al. [75], who showed that these inefficiencies greatly impede effective processes and contribute to various environmental issues. A key inefficiency highlighted in both previous research and this study is the absence of stringent policies regarding plastic waste management and the lack of adequate facilities to support recycling efforts. Inadequate waste collection and recycling infrastructure, combined with ineffective segregation practices, often results in limited public awareness of proper recycling methods and increased contamination [75]. Inefficient collection systems often lead to missed pickups, while economic barriers, such as high recycling costs and low market prices for recycled materials, discourage participation [73–76]. Inconsistent regulations and outdated technologies also complicate recycling efforts [74]. The absence of incentives for businesses and individuals, along with market fluctuations in recycled materials, creates uncertainty and undermines the sustainability of recycling programs [73–76].

4.5. Management implications, limitations, and future research

Human activities significantly alter natural ecosystems, prompting fundamental questions about the best methods for monitoring and conserving these changed environments [8–10]. In the three investigated plastic-impacted ecosystems, two located in China and one in Rwanda, factors driving environmental changes were found to be industrial and consumer practices, environmental conditions, and waste management and recycling inefficiencies. At both economic and environmental systems levels, these factors have considerable implications for policy and practice [65]. First, gaining insight into the industrial and consumer practices that contributed to plastic accumulation in the explored plastic-impacted ecosystems promotes the development of effective strategies for encouraging sustainable practices among both producers and consumers. Second, understanding the environmental conditions driving changes in these plastic-impacted ecosystems promotes the creation of standardized policies for plastic production and usage and environmental conservation efforts at the international level. Lastly, confirming waste management and recycling inefficiencies promotes data availability to improve waste management practices and enhance recycling efforts.

Limitations of this study include potential biases in data collection, constraints related to the scope of research, and the generalizability of findings. The notable bias in data collection may arise from the absence of biotic components in the analysis, which limits the understanding of nutrient leaching and the effects of nutrients on microbial communities along moisture gradients in plastic-impacted ecosystems. Addressing this gap demands distinct toxicological investigations and analyses of nutrient distribution in relationship to microbial activity and crack depths along these gradients. Another bias may be related to the study's focus on PET-dominated plastic waste. Despite the fact that PET has received considerable attention due to its dominance and its notable adverse effects on aquatic ecosystems, other identified polymers, such as ABS, HDPE, LDPE, PA, PC, PE, PP, and PS, exhibit unique chemical properties [77]. This suggests that further exploration of their interactions with clay could yield additional insights into the environmental impacts of plastic pollution. These plastics can negatively impact ecosystems in ways similar to PET, specifically by releasing micro- and nano-plastics at high concentrations and their interactions with aquatic organisms. However, current evidence suggests that, at environmentally relevant concentrations, micro- and nano-plastics associated with these polymers may not significantly threaten aquatic life [78–81]. The limitations in the scope of this research arise from the diverse sources of plastic polymers, which may not have been adequately represented in the three selected experimental field environments. With thousands of plastic polymers existing and new ones being developed regularly, it is understandable that we only identified a limited number of polymer types [82]. Specifically, we observed PET, ABS, HDPE, LDPE, PA, PC, PE, PP, and PS, as these are among the most common categories employed in various profitable activities in China and Rwanda [15–19,67]. This underrepresentation limits the generalizability of our findings across diverse countries, as ecosystems may experience the impacts of plastic pollution in distinct ways [82].

The priority scopes for further research must consider the above-shown limitations to get a broader view of our conclusions across a wide range of diverse environments in various regions.

5. Conclusions

This work uses a quantitative-qualitative system dynamics model approach to present factors driving changes in environmental systems impacted by plastic pollution. Field tests analyzing environmental changes in the unsaturated clay-rich bed and shore of a plastic-impacted pond in Shenzhen, China, and a plastic-impacted clay pit in Musanze, Rwanda, coupled with laboratory tests on plastic-reinforced clay and plastic life cycle modeling, identified three key factors: industrial and consumer practices, environmental conditions, and waste management and recycling inefficiencies.

Industrial and consumer practices drove changes in the studied plastic-impacted ecosystems by significantly increasing the inflow and accumulation of PET-dominated plastic waste. In Shenzhen, China, the accumulation of plastics in a clay-rich pond bed and shore was connected to single-use plastic items produced from various plastics, including PET, ABS, HDPE, LDPE, PA, PC, PE, PP, and PS. In Musanze, Rwanda, the accumulation of plastics in a clay pit was associated with discarded beverage bottles primarily produced from PET.

Environmental conditions drove changes in the studied plastic-impacted ecosystems by altering physicochemical and mechanical properties of clay. Cracks in the plastic-impacted clay-rich pond bed were common in areas devoid of filamentous green algae and PET-dominated plastic waste, indicating that their distribution was influenced by mulch type, thickness, and inundation. Temperature variations along the moisture gradient in the plastic-impacted clay-rich pond shore influenced moisture and nutrients, resulting in a substantial accumulation of nutrients in the more wet zone. The effects of microplastics on ecosystems, as quantified experimentally using natural clay and PET-plastics at proportions of 1.25 %, 2.5 %, 3.75 %, 5 %, and 10 % of clay weight, indicated that plastics disrupt the structure of natural clay by reducing moisture content and increasing dry density and load-bearing capacity.

Waste management and recycling inefficiencies drove changes in the studied plastic-impacted ecosystems by causing plastic waste to accumulate in the pond bed, shore, and clay pit, alongside the potential outflow of plastic litter into deeper environmental layers.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability

Data will be made available on request.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e38738.

List of abbreviations

ABS	Acrylonitrile Butadiene Styrene
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
CBR	California Bearing Ratio
MP	Modified Proctor
n	Sample size or measurements
ANOVA	Analysis of Variance
PLS-PM	Partial Least Squares Path Modeling

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