Asian Journal of Chemistry; Vol. 37, No. 10 (2025), 2477-2486

ASIAN JOURNAL OF CHEMISTRY

https://doi.org/10.14233/ajchem.2025.34390

Soil Properties as Key Determinants for the Biodegradation Kinetics of Polymer Blends in Indian Agroecosystems

DIVYANSHI MISHRA, INDU SAXENA*, ADITYA GUPTA and PREETI YADAV

Department of Chemistry, University of Lucknow, Lucknow-226007, India

*Corresponding author: E-mail: Indu_lu@yahoo.com

Received: 3 July 2025 *Accepted*: 15 September 2025 *Published online*: 30 September 2025 AJC-22132

The growing worldwide plastic pollution challenge needs the development of biodegradable polymers as potential alternatives. The present research the soil biodegradation behaviour of four polymer blends *viz*. PVA/starch, PAM/starch, PEG/HPMC and PVP/HPMC in three different Indian soil types: nutrient-rich alluvial soil (Gomti river, Lucknow), clay-rich black cotton soil (Bhopal) and nutrient-deficient mountainous soil (Kasar Devi, Almora). The PVA/starch blend exhibited the highest degradation over 28 days, with a 72% weight loss in Gomti soil, likely due to hydrophilicity of PVA and the high microbial accessibility of starch. PVP/HPMC, on the other hand, showed only minor degradation (18-35%) due to the chemical inertness of PVP. Degradation rates were found to be significantly influenced by porosity, nutrient content (Fe, Mg and K) and microbial activity, according to soil characterization using FE-SEM and EDX. The acidic pH (6.3) and compact structure of Kasar Devi soil hindered degradation, whereas the alkaline pH (7.8) and high porosity of Gomti soil facilitated favourable conditions for microbial colonization. In a range of agroclimatic zones, the present findings highlight the significance of customizing biodegradable polymers to local soil conditions, providing useful information for green packaging and agricultural films.

Keywords: Biodegradable polymers, Polymeric blends, Soil biodegradation, Green packaging.

INTRODUCTION

Plastic pollution is widely recognized as one of the most pressing environmental challenges of the 21st century. Over 300 million tons of plastic are produced annually, much of it used for short-term applications like packaging before ultimately accumulating in landfills or the natural environment [1]. Conventional petroleum-based plastics such as polyethylene (PE), polypropylene (PP) and polystyrene (PS) are resistant to microbial breakdown and can last for decades in soil and water. These resistive polymers not only affect ecosystems but also introduce microplastics, which are now often found in drinking water, food chains and even human bloodstreams [2-4].

In response, the development of biodegradable polymers has become increasingly important. These materials can decompose into water, carbon dioxide and biomass through microbial action. The shift toward biodegradables addresses two key goals for example, reducing reliance on fossil-based resources and minimizing environmental persistence of waste. Both natural polymers (*e.g.* starch, cellulose, chitosan) and synthetic alternatives (*e.g.* polyvinyl alcohol (PVA), polylactic acid (PLA), polyethylene glycol (PEG)) have been extensively studied for their biodegradability and material performance [5].

Soil biodegradation offers a practical and ecologically relevant method for evaluating the environmental fate of polymeric materials. As dynamic ecosystems, soils host diverse microbial communities, enzymes, organic matter, minerals, and moisture levels, all of which affect degradation rates [6]. Soil properties such as texture, porosity, pH, nutrient content, and microbial load vary significantly, particularly in a topographically and climatically diverse country like India, where alluvial, black cotton, and mountain soils coexist [7]. A polymer's biodegradation in soil is driven by four primary mechanisms *viz.*, surface erosion, microbial absorption, enzymatic hydrolysis and oxidative degradation. Oxygen availability further improves microbial respiration in aerobic settings, promoting quicker breakdown. In contrast, cooler or compacted soils may reduce microbial activity and slow decompo-

---

sition [8]. Thus, evaluating polymer films in soil environments indicative of several Indian biological zones is both scientifically important and contextually suitable.

Polymer blending is a common strategy in biodegradable polymer design, in which a biodegradable component is physically mixed with another polymer to customize traits such as mechanical strength, water solubility, thermal stability and biodegradability. Starch, a plant-based polysaccharide, is readily degraded by soil microbes due to its α-(1→4) and α-(1→6) glucosidic linkages. In contrast, polyvinyl alcohol (PVA), though water-soluble and partially biodegradable under aerobic conditions, degrades slowly when used alone due to its synthetic backbone and semi-crystalline structure. Blending PVA with starch enhances biodegradability by introducing easily metabolizable organic matter, which acts as a bio-trigger for microbial colonization and enzymatic activity. Starch increases the blend's hydrophilicity and water absorption, facilitating microbial access and promoting PVA chain scission through hydrolysis and oxidative cleavage. Moreover, hydrogen bonding between the hydroxyl groups of starch and PVA disrupts crystalinity, rendering the matrix more amorphous and microbially accessible. This synergistic interaction significantly improves the biodegradability of the blend compared to pure PVA [9].

Similarly, PVP/HPMC blends combine polyvinylpyrrolidone (PVP), a highly water-soluble synthetic polymer, with hydroxypropyl methylcellulose (HPMC), a biocompatible and biodegradable cellulose derivative, though the relatively recalcitrant nature of PVP can hinder overall microbial degradation despite HPMC's biodegradability [10]. Furthermore, PEG, a hydrophilic and low-toxicity polyether, may exhibit limited biodegradation when blended with HPMC, as both components are biodegradable under the specific environmental conditions; however, degradation of PEG is strongly influenced by its molecular weight and surrounding factors [11]. In contrast, polyacrylamide (PAM), another hydrophilic polymer known for its water retention and soil conditioning abilities, is generally non-biodegradable. Yet, blending PAM with starch may introduce enzymatically accessible sites, enhancing its breakdown under favourable microbial conditions [12].

India's climatic and geographic diversity results in varied soil types with distinct chemical and physical properties. In this study, soil samples were collected from three different locations *e.g.*, (i) Gomti river banks (Lucknow city), which consists of nutrient-rich alluvial soil with high organic and microbial content; (ii) Bhopal city, situated in the middle of India, has clay-rich black cotton soil, dense, moisture-retentive and poorly aerated; and (iii) Kasar Devi (Almora city), where a high-altitude soil with low nutrients, low temperatures and reduced microbial density.

In present study, four polymeric blends were prepared for evaluation, *viz*. polyvinyl alcohol/starch (PVA/starch); polyvinylpyrrolidone/hydroxypropyl methylcellulose (PVP/HPMC); polyethylene glycol/hydroxypropyl methylcellulose (PEG/HPMC); and polyacrylamide/starch (PAM/starch). Each combination was chosen to reflect a distinct ratio of synthetic and natural polymer contributions.

This study presents a comprehensive evaluation of polymeric blend degradation by examining changes in the hydrophilicity and polymer chemistry, soil morphology and elemental composition, and regional environmental factors such as temperature, moisture, and microbial density. The findings have practical relevance for designing biodegradable packaging and agricultural films tailored to India's diverse agroclimatic zones. Given the country's growing waste burden and limited waste management infrastructure in rural areas, soil-specific biodegradable films offer a sustainable alternative to conventional plastics. By integrating soil science, polymer chemistry and material characterization, this research advances ecologically adaptive biomaterials and supports national initiatives like Swachh Bharat Abhiyan and the Plastic Waste Management Rules.

EXPERIMENTAL

The polymers utilized to make the polymeric blend films were polyvinyl alcohol (PVA), polyacrylamide (PAM), polyethylene glycol (PEG), polyvinylpyrrolidone (PVP), starch and hydroxypropyl methylcellulose (HPMC). All chemicals were of analytical grade and acquired from Sigma-Aldrich in India. Distilled water was employed as solvent for the entire solutions preparation.

Preparation of polymer blend solutions: Polymeric blend films were prepared using the solvent casting method, following standardized procedures for each composition. For the PVA/starch blend, 0.01 M starch (MW 342.3 g/mol) was dissolved in 100 mL of hot conductivity-grade distilled water with continuous stirring, followed by gradual addition of 0.5 g PVA at 60-70 ºC. The PAM/starch blend was prepared similarly, with 0.01 M starch dissolved in 100 mL hot distilled water, then mixed with 2 g PAM under constant stirring. For the HPMC/PVP blend, 1 g HPMC was dissolved in 50 mL of hot distilled water (~70 ºC), followed by the addition of 50 mL cold distilled water and 2 g PVP, yielding a clear and homogeneous solution. The HPMC/PEG blend was prepared using the same HPMC procedure, with 2 g PEG added and stirred until uniform. All blend solutions were cast into silicone molds and solvent was evaporated on water bath form thin, flexible films suitable for biodegradation testing.

Soil samples collection: Soil samples were collected from three ecologically diverse regions in India to provide a range of microbiological and physico-chemical conditions for the degradation investigation. The initial soil sample was gathered from the Gomti river bank in Lucknow, Uttar Pradesh (S1), which is well-known for its fertile alluvial soil rich in organic matter. The second soil sample was collected in Bhopal city (S2) and consisted of black cotton soil with moderate nutritional content and water-holding capability. Third sample was collected from Kasar Devi, Almora, (S3) and represents a Himalayan soil with low nutrient availability, acidic pH and compact texture.

The soils were air-dried, filtered through a 2 mm sieve to remove big debris and stored in sterile vessels at room temperature until use. Before the degradation experiment, the physico-chemical factors such as soil pH, moisture content and elemental composition were assessed.

Soil burial degradation process: The degradation experiment was carried out by burying different polymeric blend films in soil taken from various locations of India. The soil was put in a 3 cm beaker depth. Soil samples were dried, then combined with distilled water. The mixture was agitated violently for 30 min before settling for 60 min. Following filtration, the suspension was centrifuged five to six times at 3000 rpm. The moisture content of the soil was maintained by adding water at regular intervals. The rate of degradation of films was monitored over time. The amount of biodegradation was determined by calculating the % weight loss using the following formula:

$$\text{Weight loss (\%)} = \frac{W_o - W_t}{W_o} \times 100$$

where W_o = the weight of polymeric film at the initial stage and W_t is the weight of the polymeric film after a specific period of biodegradation.

Characterization: Field emission scanning electron microscopy (FE-SEM) was used to examine the surface morphology changes in polymeric films before and after degradation, using a Hitachi S-3400N (JEOL JSM 7610F) at 10 kV. Film samples were gold-coated *via* sputtering to the enhance conductivity and images were captured at various magnifications. Soil samples from all three locations were similarly sputter-coated and mounted on aluminum stubs for FE-SEM analysis to assess particle size, texture and porosity. Moreover, energy dispersive X-ray spectroscopy (EDX) was performed using the same setup to quantify the elemental composition specifically O, Si, Al, Fe, K, Ca, and Mg, which was correlated with biodegradation potential to understand the influence of soil mineral content on microbial activity.

Soil pH measurement: To test soil pH, a 1:2.5 suspension of soil and distilled water was prepared. The suspension was well agitated and left to settle for 30 min. A digital pH meter was used to record pH data. Each soil sample was measured in triplicate and the average value was reported.

RESULTS AND DISCUSSION

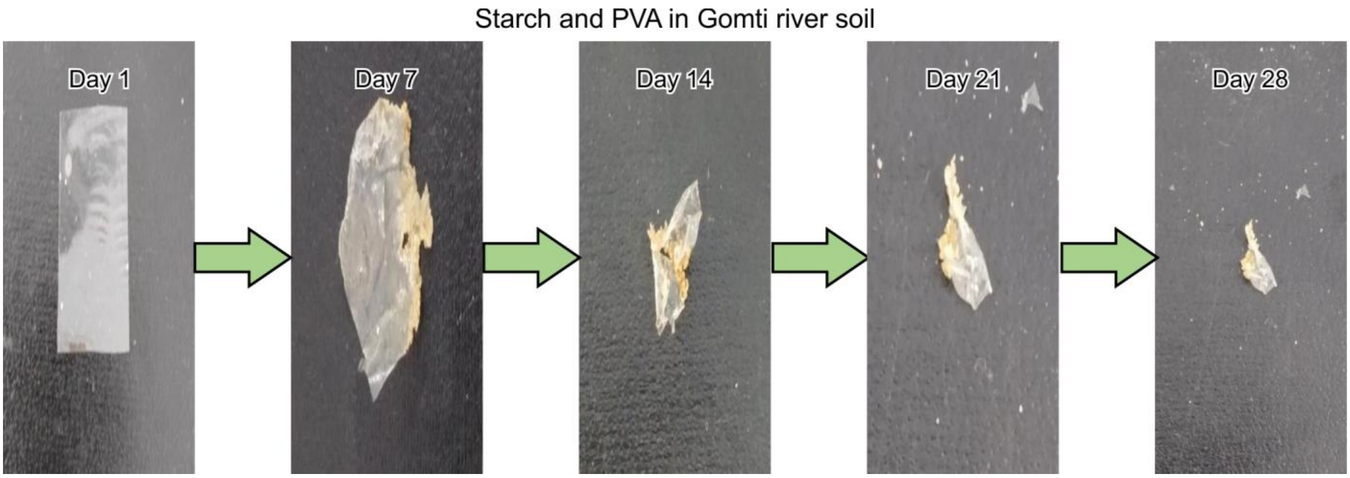
Biodegradation pattern of polymeric blend films in different soils: The biodegradation pattern of the prepared polymeric blend films in natural soils was determined by a variety of parameters, including polymer content, soil microbial diversity, ambient conditions and soil physico-chemical parameters. In the current investigation, the % weight loss of four different polymeric blend films, PVA/starch, PAM/starch, PEG/HPMC and PVP/HPMC, was measured over a 28-day period across three soil samples with different ecological characteristics.

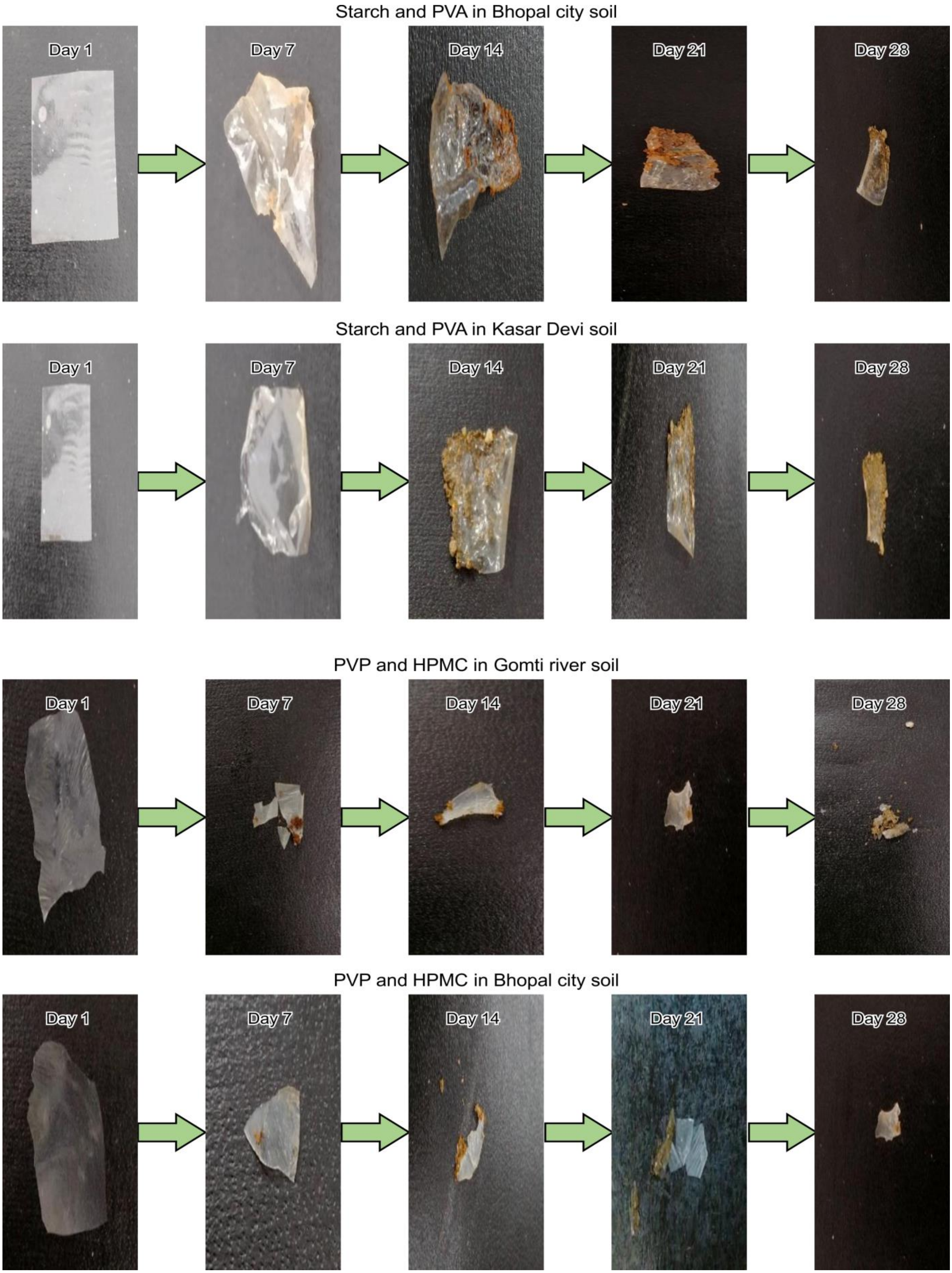
Among all blends, the PVA/starch film degraded the fastest, with weight loss reaching 72% in Gomti river soil, 61% in Bhopal city soil and 45% in Kasar Devi soil (Fig. 1). The improved degradability of polymeric blend can be assigned to the biodegradable property of starch, that serves as an instantaneous carbon source for soil microbes [13] and the hydrophilic and partially degradable properties of PVA, which undergoes the microbial assimilation following oxidative chain scission under aerobic conditions [14]. The addition of starch into the PVA matrix improves overall water uptake and microbial colonization by producing microvoids during swelling and leaching processes [15].

The PAM/starch combination degraded moderately, with rates ranging from 32 to 55% depending on soil type. Although PAM is a synthetic polymer with low biodegradability due to its chemically inert amide groups [16], the inclusion of starch introduces enzymatically cleavable glycosidic linkages, hastening the initial matrix disintegration [17]. Through increased surface area exposure and physical disintegration, microbial use of starch probably disturbs the polymer network, which in turn promotes the deterioration of the surrounding PAM phase.

The PEG/HPMC combination had an analogous intermediate degradation pattern. Polyethylene glycol (PEG), depending on its molecular weight, is vulnerable to microbial oxidation, particularly when present in low-molecular-weight fractions [18]. The addition of HPMC, a water-soluble and sustainable cellulose derivative, enhanced film degradability by increasing hydrophilicity and water retention [19]. The blend lost 28-40% of its weight during the research period, with outstanding results in the rich in nutrients Gomti soil.

PVP/HPMC, on the other hand, showed the slowest rate of degradation, with weight loss varying between 18 and 35%. PVP is characterized by its chemical stability, large molecular weight and ability to withstand microbial attack due to its N-vinylpyrrolidone backbone [20]. Although HPMC is biodegradable, its limited proportion in the blend was insufficient to offset the inert nature of PVP; moreover, hydrophobic


Starch and PVA in Gomti river soil



Starch and PVA in Bhopal city soil

Starch and PVA in Kasar Devi soil

PVP and HPMC in Gomti river soil

PVP and HPMC in Bhopal city soil

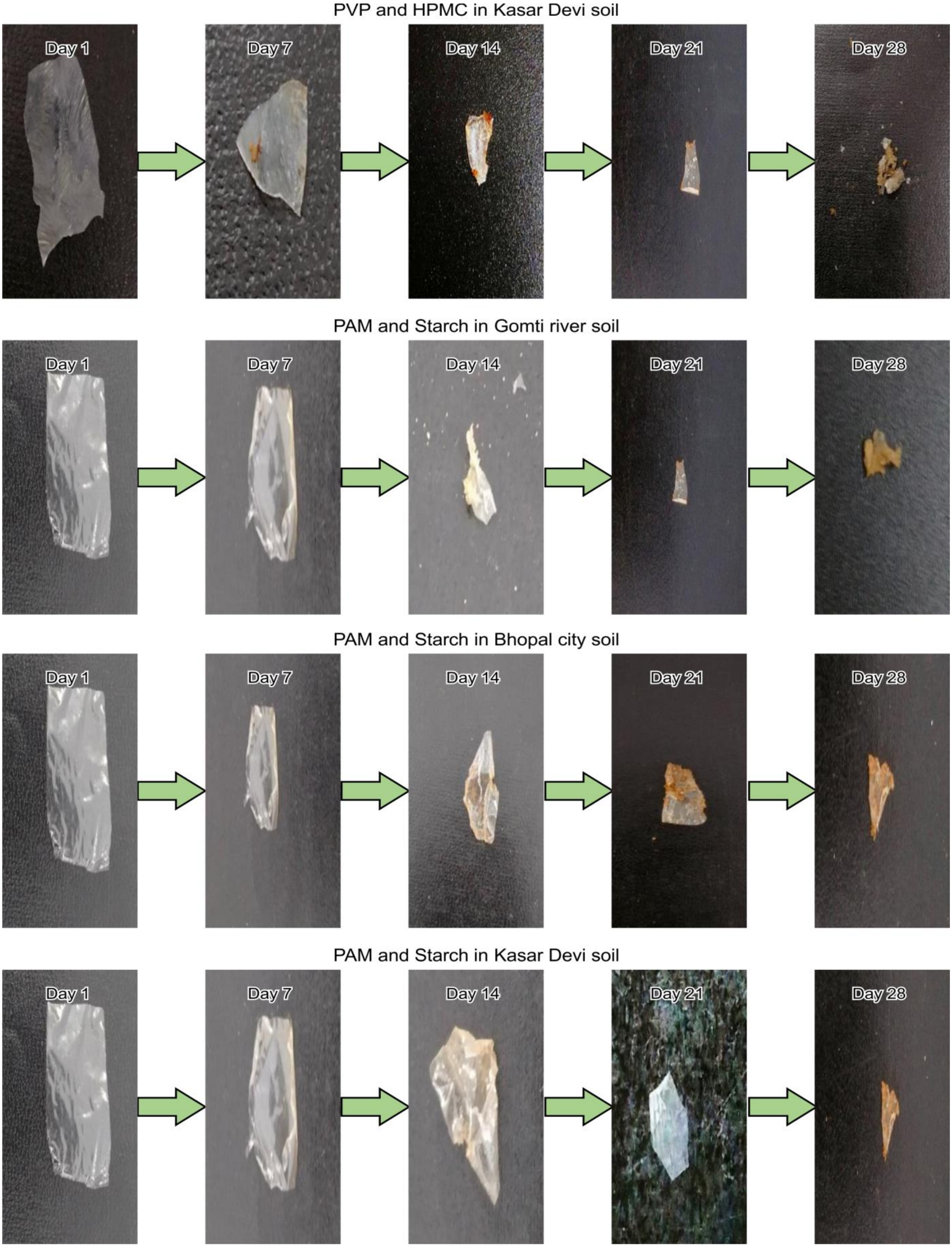


Fig. 1. Biodegradation trend of polymeric samples in different soil

interactions between PVP chains may further hinder microbial enzyme access, reducing overall degradation.

The degradation kinetics studied revealed that polymeric films containing natural polysaccharides (such as starch) and hydrophilic synthetic polymers (PVA and PEG) degrade faster. The soil microbial load, as well as environmental conditions like moisture and oxygen availability, influence these rates. Previous studies [21,22] support these findings, indicated that blends with higher renewable content disintegrate faster under soil burial conditions. Furthermore, degradation curves demonstrated a soil-dependent pattern, with Gomti river bank soil permitting the fastest deterioration, followed by Bhopal city and then Kasar Devi soil. This sequential pattern emphasizes the importance of soil type on polymer breakdown, which is typically overlooked in the laboratory-based biodegradation investigations.

PVA/starch blend films: Prior to soil burial, the PVA/starch blend films showed no obvious pores or imperfections and a homogeneous, smooth and crack-free surface morphology. Significant morphological alterations were observed following 28 days of soil exposure; the degree of these changes varied according to the particular type of soil.

The PVA/starch films in soil of the Gomti river showed deep fissures, broad microbial colonization zones and severe surface erosion (Fig. 2a). This is consistent with the soil's greatest weight decrease (~72%). The microbial breakdown of both starch and PVA components was greatly expedited by the loose and porous quality of Gomti soil, as well as by its nutrient-rich composition and high microbial density [23].

In Bhopal city soil, the FE-SEM images showed sporadic microbial attachment sites, shallow fissures and mild surface roughening (Fig. 2b). In comparison to Gomti soil, the degradation rate was somewhat lower (~61%) due to the restricted microbial mobility caused by the thicker and less porous texture of Bhopal soil.

The FE-SEM images of Kasar Devi soil revealed little microbial colonization and little surface erosion (Fig. 2c). The fine-grained, compact structure of this soil, combined with its low microbial load and limited nutrient availability, hindered microbial accessibility, resulting in the lowest degradation (~45%) among the three soils tested for this blend. These findings reinforce that the degradation of the PVA/starch blend was largely soil-dependent, with microbial activity and soil porosity playing key roles.

PVP/HPMC blend films: After 28 days of burial in Gomti river soil, the PVP/HPMC film showed only minimal surface roughening and shallow pits (Fig. 3a), indicating limited microbial penetration despite the favourable microbial environment of soil. The high molecular weight and chemical stability of PVP likely hindered enzymatic degradation [24]. In Bhopal city soil, the film surface remained largely intact, with only minor etching observed at high magnification (Fig. 3b), suggesting that moderate porosity and microbial activity were insufficient for significant breakdown. In Kasar Devi soil, FE-SEM images revealed negligible changes, and the film retained its smooth surface (Fig. 3c), with low degradation (18-35% weight loss) attributed to soil compaction, low nutrient levels, and the inherent resistance of PVP. Overall, PVP/HPMC films exhibited consistently low degradation across all soils, with surface morphology indicating poor environmental biodegradability under natural conditions.

PEG/HPMC blend films: FE-SEM analysis of the PEG/HPMC polymeric blend film in Gomti river soil revealed the moderate surface erosion, thin fissures and localized microbial growth zones (Fig. 4a), likely driven by the hydrophilic nature of PEG, the biodegradability of HPMC, and the soil's rich microbial and nutrient profile [25]. In contrast, Bhopal city soil-treated films exhibited less surface degradation, showing only minor pits and moderate roughness (Fig. 4b), attributed to limited oxygen diffusion and microbial mobility caused by the soil's compact structure. Interestingly, despite its low nutrient content, Kasar Devi soil showed greater surface cracking and erosion than Bhopal soil (Fig. 4c), possibly due to the water-retaining properties of PEG, which may have maintained localized moisture around the film, fostering microbial activity even under low-porosity conditions [26]. These observations align with the measured degradation rates, highlighting the influence of soil type on both the extent and nature of PEG/HPMC film degradation.

PAM/starch blend films: After 28 days of soil burial, PAM/starch films in Gomti river soil showed surface roughening, large pores, and visible microbial colonies (Fig. 5a),

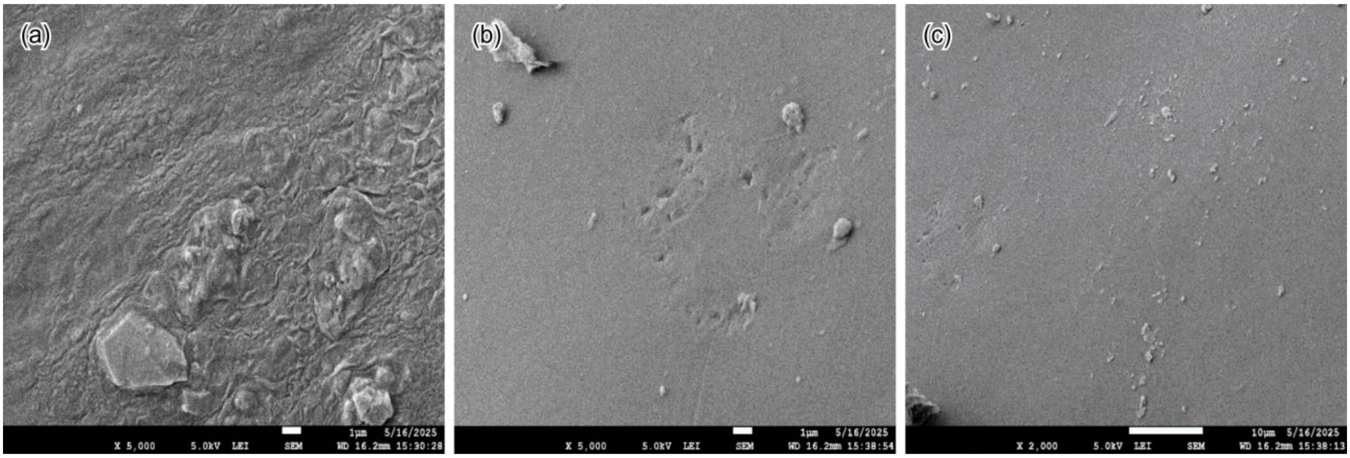


Fig. 2. FE-SEM micrographs of PVA/starch blend films after 28-day soil burial (a) Gomti river soil, (b) Bhopal city soil and (c) Kasar Devi soil

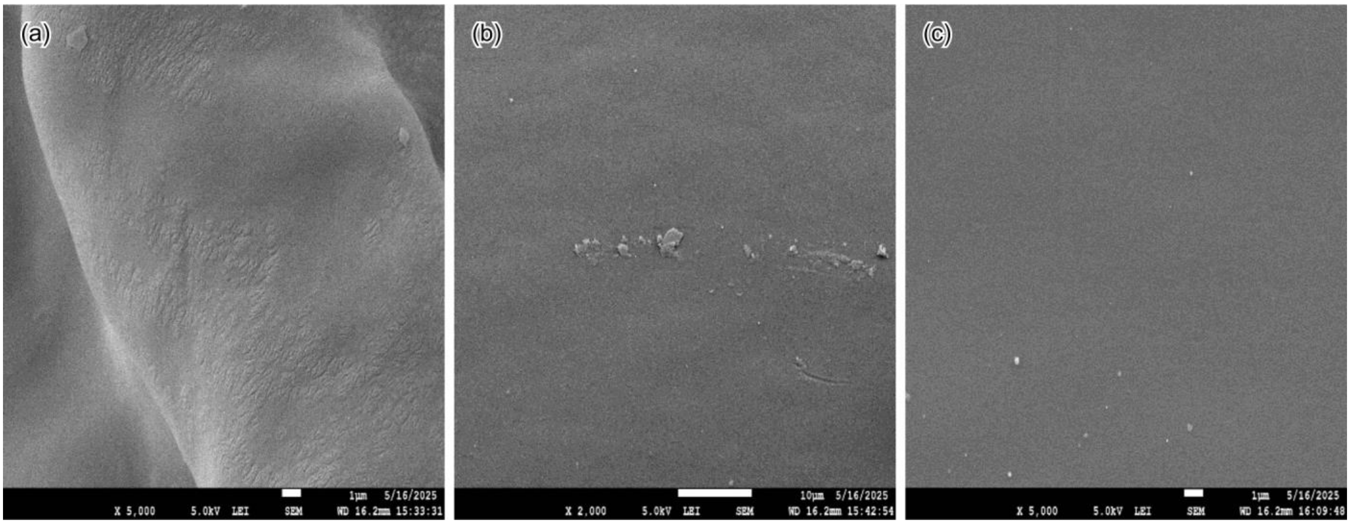


Fig. 3. FE-SEM micrographs of PVP/HPMC blend films after 28-day soil burial (a) Gomti river soil, (b) Bhopal city soil and (c) Kasar Devi soil

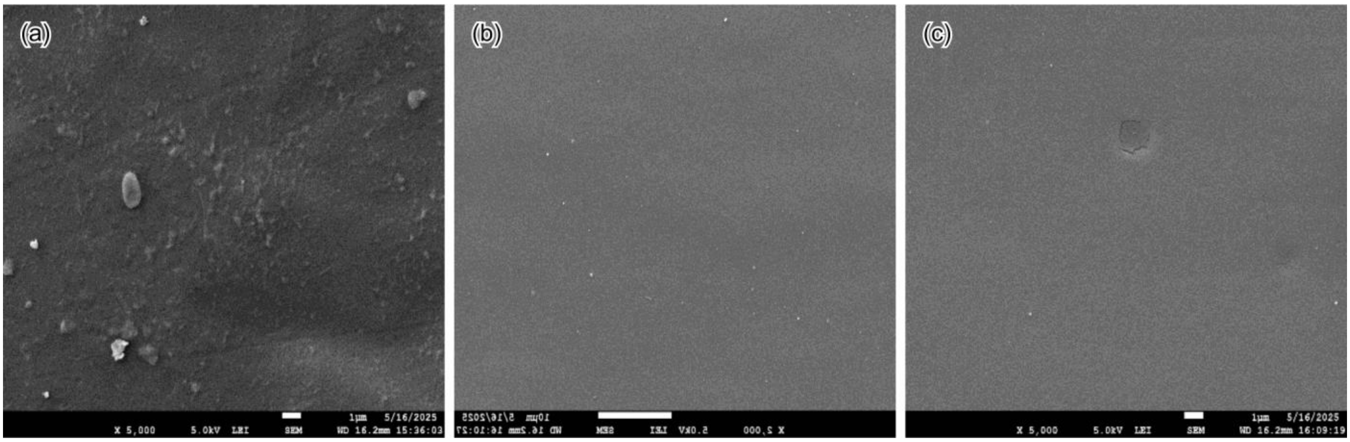


Fig. 4. FE-SEM micrographs of PEG/HPMC blend films after 28-day soil burial (a) Gomti river soil, (b) Bhopal city soil and (c) Kasar Devi soil

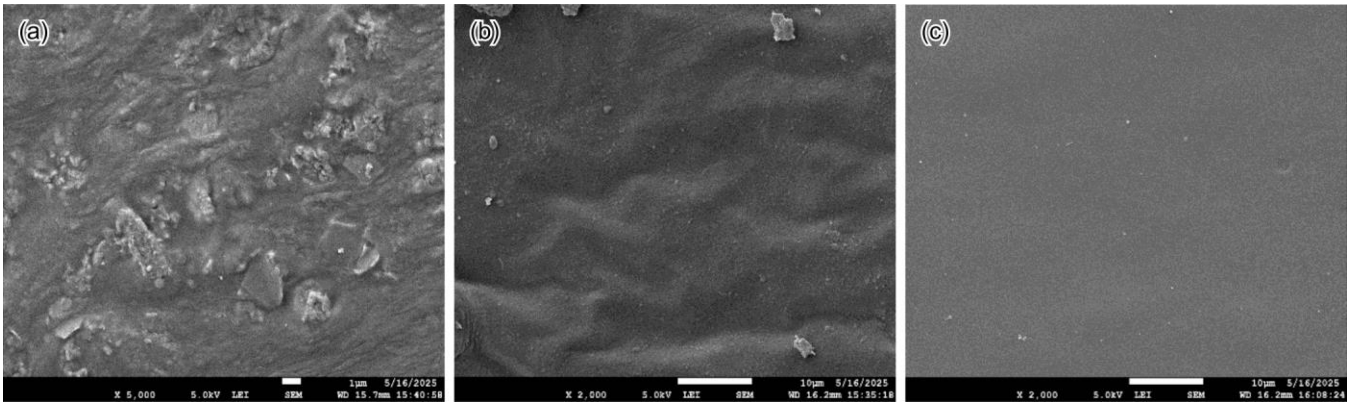


Fig. 5. FE-SEM micrographs of PAM/starch blend films after 28-day soil burial (a) Gomti river soil, (b) Bhopal city soil and (c) Kasar Devi soil

with the soil's high porosity and nutrient content facilitating microbial access and starch degradation, along with the partial physical disruption of PAM. In Bhopal city soil, FE-SEM images revealed significant surface cracking and roughening but fewer pores and reduced microbial colonization compared to Gomti river (Fig. 5b), resulting in a lower degradation rate of about 48% due to the compact soil's limited microbial activity. Kasar Devi soil showed minimal surface changes (Fig. 5c), likely caused by poor porosity and nutrient scarcity restricting microbial growth and enzymatic breakdown. Overall, starch primarily drove the degradation of PAM/starch polymeric films, while soil characteristics governed microbial accessibility and the degree of surface erosion, consistent with prior findings that soil oxygenation and microbial activity are key to degrading starch-based polymer blends [27].

EDX analysis: Energy Dispersive X-ray Spectroscopy (EDX) analysis provided detailed insights into the elemental composition of the soil samples, which influenced microbial activity and biodegradation rates. Gomti river soil contained high levels of Fe, Mg, K, Ca, and Si elements known to support microbial growth and enzymatic function (Fig. 6a). In particular, iron and magnesium enhance microbial respiration and enzyme cofactor production, accelerating polymer degradation [28]. Bhopal city soil exhibited moderate amounts of Fe, Al and Si but lower Ca and K compared to Gomti river, with its compact structure contributing to slower biodegradation (Fig. 6b). Kasar Devi soil showed the lowest concentrations of key elements, with barely detectable Fe, K, and S levels (Fig. 6c), likely limiting microbial proliferation and enzymatic activity, resulting in the poorest biodegradation. These EDX results highlighted the critical role of soil mineralogy in regulating microbial activity and polymer blend degradation rates [29].

Relationship between porosity and biodegradation rate: Soil porosity is a crucial factor influencing the rate and extent of polymer biodegradation. Under aerobic conditions, factors such as oxygen diffusion, water retention, microbial migration, and substrate availability, all directly affected by porosity, govern polymer breakdown [30]. Estimated porosity values for the soils studied were approximately 50% for Gomti river soil, 35% for Bhopal city soil and 20% for Kasar Devi soil, based on FE-SEM images and literature data. The granular, loose texture (Fig. 7a) of Gomti river supports high porosity, facilitating optimal air and moisture flow and promoting the aerobic microbial growth, which, combined with favourable nutrients, resulted in the highest degradation rates across all polymer blends [31]. In contrast, Bhopal city soil's moderate porosity (Fig. 7b) limited oxygen and moisture penetration, reducing biodegradation compared to Gomti river, particularly affecting the polymeric blends with lower hydrophilicity like PEG/HPMC and PAM/starch. Kasar Devi soil, with its compact, fine-grained structure and lowest porosity (~20%, Fig. 7c), created a physical barrier that restricted oxygen and microbial access, leading to the slowest degradation rates [32]. Across all polymeric blends, a clear positive correlation emerged between soil porosity and biodegradation rate, as higher porosity enhances microbial colonization and enzyme substrate interactions on the polymer surfaces [33]. These findings align with prior studies linking increased soil porosity to greater microbial activity and faster organic matter turnover [34].

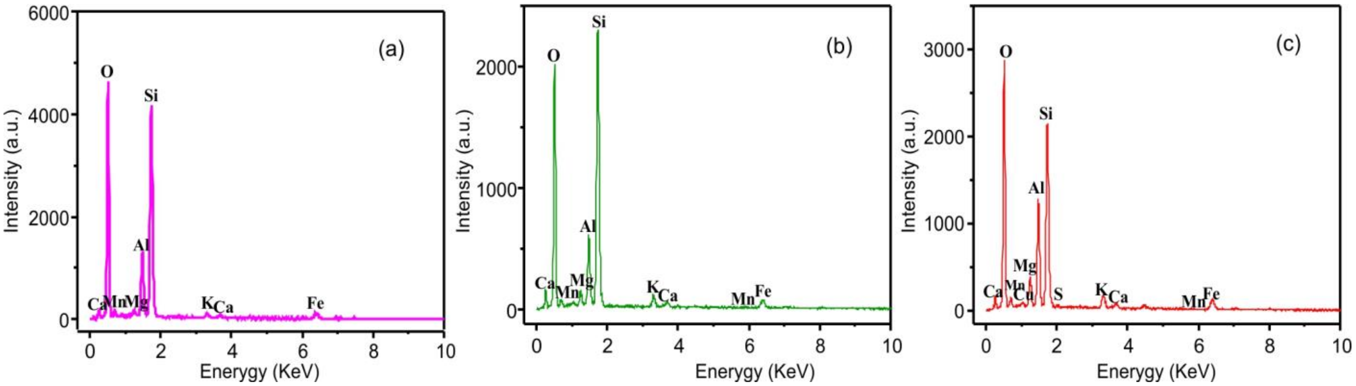


Fig. 6. EDX elemental maps of soils: (a) Gomti river soil, (b) Bhopal city soil and (c) Kasar Devi soil (depleted Fe, K and S; dominated by Si/Al)

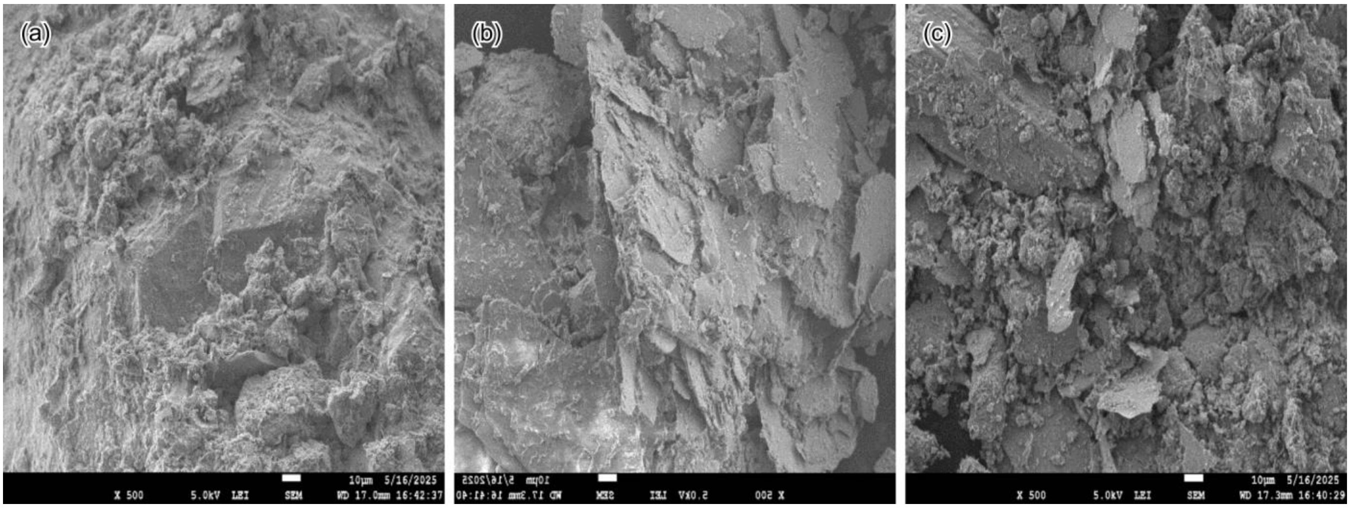


Fig. 7. FE-SEM micrographs of soil samples highlighting porosity differences: (a) Gomti river alluvial soil, (b) Bhopal city black cotton soil and (c) Kasar Devi mountainous soil

Soil pH and its influence on biodegradation: Soil pH plays a critical role in shaping microbial community structure, enzyme activity and the overall biodegradation efficiency of polymeric materials in terrestrial environments. The three soil samples in this study exhibited varying pH levels, each influencing the degradation behavior of the polymer blend films. Gomti river soil had a slightly alkaline pH of 7.8, creating an optimal environment for diverse bacteria and fungi involved in polymer breakdown. Bhopal city soil, with a neutral to mildly alkaline pH of 7.2, similarly supported favourable conditions for extracellular enzymes such as amylases, cellulases and oxidoreductases, which are essential for polymer degradation [35,36]. In contrast, Kasar Devi soil showed a slightly acidic pH of 6.3, which likely hindered the microbial proliferation and enzyme function. Acidic conditions can suppress microbial diversity and reduce the activity of oxidative and hydrolytic enzymes, contributing to the slower degradation rates observed across all polymer blends in this soil [37-39]. These results underscore the importance of soil pH as a key abiotic factor influencing the environmental fate of biodegradable polymers.

Conclusion

This study highlights the critical role of soil-specific factors such as nutrient composition, porosity, pH and microbial diversity in influencing the biodegradation of polymeric blends. Among the tested materials, the PVA/starch blend exhibited the highest degradation rates (over 70%) in the nutrient-rich, porous soils, making it the most environmenttally viable, while PVP/HPMC showed only moderate compatibility. The findings underscore the interplay between polymer chemistry (*e.g.* hydrolyzable bonds of starch *vs.* recalcitrance of PVP) and soil ecology, reinforcing the need for regionally adapted biodegradable materials. For instance, soils like those near the Gomti river promote the rapid degradation, whereas compact or acidic soils may require blends with enhanced hydrophilicity or enzymatic responsiveness. These insights align with India's Swachh Bharat Abhiyan and global sustainability efforts by supporting localized, eco-friendly alternatives to the conventional plastics. Future research should focus on microbial consortia and enzyme-driven enhancements to improve degradation in challenging soil environments, advancing the circular economy model for the plastic waste management.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the Head, oDepartment of Chemistry, University of Lucknow, Lucknow, India, for providing the research laboratory facilities. The authors also extend their thanks to the Director, Birbal Sahni Institute of Palaeosciences, Lucknow, India, for granting the permission to utilize the FE-SEM and EDX instrumentation facilities.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. R.U. Halden, *Annu. Rev. Public Health*, **31**, 179 (2010); https://doi.org/10.1146/annurev.publhealth.012809.103714
2. R. Geyer, J.R. Jambeck and K.L. Law, *Sci. Adv.*, **3**, e1700782 (2017); https://doi.org/10.1126/sciadv.1700782
3. S.L. Wright and F.J. Kelly, *Environ. Sci. Technol.*, **51**, 6634 (2017); https://doi.org/10.1021/acs.est.7b00423
4. L. Lebreton, B. Slat, F. Ferrari, B. Sainte-Rose, R. Marthouse, J. Aitken, S. Hajbane, S. Cunsolo, A. Schwarz, A. Levivier, K. Noble, P. Debeljak, H. Maral, R. Schoeneich-Argent, R. Brambini and J. Reisser, *Sci. Rep.*, **8**, 4666 (2018); https://doi.org/10.1038/s41598-018-22939-w
5. I.N. Vikhareva, E.A. Buylova, G.U. Yarmuhametova, G.K. Aminova, and A.K. Mazitova, *J. Chem.*, **2021**, 5099705 (2021); https://doi.org/10.1155/2021/5099705
6. S. Sharma and S. Chatterjee, *Environ. Sci. Pollut. Res. Int.*, **24**, 21530 (2017); https://doi.org/10.1007/s11356-017-9910-8
7. S.P. Singh, S. Dutta, S. Jha, S.S. Prasad, S.K. Chaudhary, M.C. Manna, K. Majumdar, P. Srivastava, P.S. Brahmanand, K.M. Singh and K. Kumar, *Sustainability*, **14**, 11585 (2022); https://doi.org/10.3390/su141811585
8. N. Lucas, C. Bienaime, C. Belloy, M. Queneudec, F. Silvestre and J.-E. Nava-Saucedo, *Chemosphere*, **73**, 429 (2008); https://doi.org/10.1016/j.chemosphere.2008.06.064
9. G. Kale, R. Auras, S.P. Singh and R. Narayan, *Polym. Test.*, **26**, 1049 (2007); https://doi.org/10.1016/j.polymertesting.2007.07.006
10. A.M. Elgarahy, K.Z. Elwakeel, S.H. Mohammad and G.A. Elshoubaky, *J. Environ. Chem. Eng.*, **8**, 103915 (2020); https://doi.org/10.1016/j.jece.2020.103915
11. M. Vert, Y. Doi, K.-H. Hellwich, M. Hess, P. Hodge, P. Kubisa, M. Rinaudo and F. Schué, *Pure Appl. Chem.*, **84**, 377 (2012); https://doi.org/10.1351/PAC-REC-10-12-04
12. S.J. Joshi and R.M.M. Abed, *Environ. Process*, **4**, 463 (2017); https://doi.org/10.1007/s40710-017-0224-0
13. A.A. Shah, F. Hasan, A. Hameed and S. Ahmed, *Biotechnol. Adv.*, **26**, 246 (2008); https://doi.org/10.1016/j.biotechadv.2007.12.005
14. A. Chamas, H. Moon, J. Zheng, Y. Qiu, T. Tabassum, J.H. Jang, M. Abu-Omar, S.L. Scott and S. Suh, *ACS Sustain. Chem.& Eng.*, **8**, 3494 (2020); https://doi.org/10.1021/acssuschemeng.9b06635
15. J.G. Rosenboom, R. Langer and G. Traverso, *Nat. Rev. Mater.*, **7**, 117 (2022); https://doi.org/10.1038/s41578-021-00407-8
16. E.R. Rene, P.K. Sarangi, V. Sànchez i Nogué, A. Schnürer and D. Salvachúa, *Microb. Biotechnol.*, **16**, 173 (2023); https://doi.org/10.1111/1751-7915.14198
17. V. Tournier, C.M. Topham, A. Gilles, B. David, C. Folgoas, E. Moya-Leclair, E. Kamionka, M.-L. Desrousseaux, H. Texier, S. Gavalda, M. Cot, E. Guémard, M. Dalibey, J. Nomme, G. Cioci, S. Barbe, M. Chateau, I. André, S. Duquesne and A. Marty, *Nature*, **580**, 216 (2020); https://doi.org/10.1038/s41586-020-2149-4
18. J.J. Kim, S.S. Lee, P. Fenter, S.C.B. Myneni, V. Nikitin and C.A. Peters, *Environ. Sci. Technol.*, **57**, 3104 (2023); https://doi.org/10.1021/acs.est.2c07678
19. S. Zhang, Z. Li, J. Shu, H. Xue, K. Guo and X. Zhou, *Microbiome*, **10**, 97 (2022); https://doi.org/10.1186/s40168-022-01290-3
20. H.F. Son, I.J. Cho, S. Joo, H. Seo, H.Y. Sagong, S.Y. Choi, S.Y. Lee, and K.J. Kim, *ACS Catal*., **9**, 3519 (2019); https://doi.org/10.1021/acscatal.9b00568
21. S.S. Ali, T. Elsamahy, D. Zhu and J. Sun, *J. Hazard. Mater.*, **443**, 130287 (2023); https://doi.org/10.1016/j.jhazmat.2022.130287
22. N. Mohanan, Z. Montazer, P.K. Sharma, and D.B. Levin, *Front. Microbiol.*, **11**, 580709 (2020); https://doi.org/10.3389/fmicb.2020.580709
23. Q. Fan, L. Wang, Y. Fu, Q. Li, Y. Liu, Z. Wang and H. Zhu, *Sci. Total Environ.*, **856**, 159003 (2023); https://doi.org/10.1016/j.scitotenv.2022.159003

24. Z. Dan, Y. Che, X. Wang, P. Zhou, Z. Han, D. Bu, X. Lu, W. Ma and G. Chen, *Environ. Res.*, **216**, 114681 (2023); https://doi.org/10.1016/j.envres.2022.114681
25. C. Jehanno, J.W. Alty, M. Roosen, S. De Meester, A.P. Dove, E.Y.-X. Chen, F.A. Leibfarth and H. Sardon, *Nature*, **603**, 803 (2022); https://doi.org/10.1038/s41586-021-04350-0
26. Y. Wang, B. Wu, X. Zheng, B. Chen and C. Chu, *Water Res.*, **229**, 119450 (2023); https://doi.org/10.1016/j.watres.2022.119450
27. P.-P Wang, F. Zhang and S. Sun, *Mar. Pollut. Bull.*, **186**, 114462 (2023); https://doi.org/10.1016/j.marpolbul.2022.114462
28. B. Ru, J. Huang, Y. Zhang, K. Aldape and P. Jiang, *Nat. Commun.*, **14**, 568 (2023); https://doi.org/10.1038/s41467-023-36062-6
29. W. Tong, H. Fang, K. Song, X. Xie, J. Wang, Y. Jin, S. Wu, J. Hu and Q. Chu, *Carbohydr. Polym.*, **299**, 120182 (2023); https://doi.org/10.1016/j.carbpol.2022.120182
30. X. Zhao, B. Lyu, L. Zhang, J. Li, Y. Zhao, Y. Wu and Z. Shi, *J. Hazard. Mater.*, **443**, 130223 (2023); https://doi.org/10.1016/j.jhazmat.2022.130223
31. J.L. García, *Microb. Biotechnol*., **15**, 2699 (2022); https://doi.org/10.1111/1751-7915.14114
32. M. Pagani, D. Gutierrez-Barragan, A.E. de Guzman, T. Xu and A. Gozzi, *Commun. Biol.*, **6**, 1238 (2023); https://doi.org/10.1038/s42003-023-05629-w
33. Y. Orhan, H. Hrenović and H. Büyükgüngör, *Acta Chim. Slov.*, **51**, 579 (2004).
34. A. Popenda, E. Wiśniowska and C. Manuel, *Desalin. Water Treatment*, **319**, 100456 (2024); https://doi.org/10.1016/j.dwt.2024.100456
35. N. Fierer and R.B. Jackson, *Proc. Natl. Acad. Sci. USA*, **103**, 626 (2006); https://doi.org/10.1073/pnas.0507535103
36. A. Sivan, *Curr. Opin. Biotechnol*., **22**, 422 (2011); https://doi.org/10.1016/j.copbio.2011.01.013
37. S. Barron and E.J. Rugel, *Environ. Sci. Policy*, **139**, 1 (2023); https://doi.org/10.1016/j.envsci.2022.10.005
38. H.-X. Wang, W.L. Toh, B.Y. Tang and Y. Surendranath, *Nat. Catal.*, **6**, 335 (2023); https://doi.org/10.1038/s41929-023-00944-1
39. K.P. Sullivan, A.Z. Werner, K.J. Ramirez, L.D. Ellis, J.R. Bussard, B.A. Black, D.G. Brandner, F. Bratti, B.L. Buss, X. Dong, S.J. Haugen, M.A. Ingraham, M.O. Konev, W.E. Michener, J. Miscall, I. Pardo, S.P. Woodworth, A.M. Guss, Y. Román-Leshkov, S.S. Stahl and G.T. Beckham, *Science*, **377**, 1095 (2022); https://doi.org/10.1126/science.abo4626