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Original Research

Potential Pollution by Biodegradable Waste: Assessing the Degradability of Oxo-degradable, Compostable, and Biodegradable Products Under Laboratory Conditions

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ABSTRACT

This study evaluated the degradability of three products, an oxo-degradable garbage bag (GB), a compostable lunch sheet (LS), and a biodegradable salad plate (SP) under four controlled laboratory simulations representing natural environmental scenarios of a freshwater body (FW), river bank (RS), landfill (COM), and direct ultraviolet (UV) light exposure. Degradation was assessed over time by monitoring weight changes monthly. Mechanical and chemical changes were monitored using tensile strength testing and Fourier Transform Infrared (FT-IR) spectroscopy, respectively. Among the tested products, SP exhibited the highest mean percentage weight loss (43.76±3.34 - 100%) under RS. Instead of weakening, GB exhibited increased Mean Tensile Strength at Break and Mean Elongation at Break under RS (7.25±0.29 and 317.78±9.15, respectively) and COM (4.35±0.88 and 46.16±28.11, respectively), suggesting possible crosslinking or physical ageing rather than degradation. No loss of characteristic peaks indicating biodegradation of the polymer material was observed in SP under FW and UV exposures, in LS under UV exposure, and in GB under FW, RS, or COM exposures. The findings highlight that degradation rates vary substantially across media types and sample materials. The potential contribution of certain biodegradable materials, particularly oxo low-density polyethylene (oxo-LDPE), to long-term plastic pollution is emphasized.

INTRODUCTION

Mismanaged domestic plastic waste pollutes the environment, challenging efforts towards sustainable waste management. Given their persistent nature, plastics accumulate when improperly discarded. Research on biodegradable synthetic polymers began in the early 1980s (Orhan et al. 2004), and were designed to remain inert to selected environmental factors during use, but to biologically degrade once disposed of (Itävaara et al. 2002). Therefore, these are introduced as an eco-friendly solution to mitigate the deleterious impacts of waste plastic accumulation. Ahmed et al. (2018) classified biodegradable plastics into three categories: fossil-based, bio-based, and biodegradable polymer blends. Fossil-based biodegradable plastics are derived from fossil fuels and used mainly in the packaging industry, while bio-based biodegradable plastics are derived from renewable sources. Biodegradable polymer blends are produced by blending different materials with desirable biodegradation characteristics.

Any alteration in the physical or chemical properties of polymers due to environmental factors, including light, moisture, heat, or biological activity, can be described as polymer degradation. Venkatesh et al. (2021) suggested three types of polymer-degrading methods based on the factors involved: thermo-oxidative degradation, photo-degradation, and biodegradation. Thermo-oxidative degradation involves the degradation of polymers in the presence of oxygen-enriched environments, initiated by the reaction of free radicals produced via polymerization (Gijsman, 2008). Photo-degradation is the combined effect of sunlight and air that causes oxidation and hydrolysis. Based on the compounds involved, photo-degradation can be direct or indirect. Micropollutants undergo direct photolysis when the light is absorbed under the deployed irradiation conditions. Indirect photodegradation occurs when photosensitizers are present. Biodegradation is the partial or complete conversion of polymers into CO_2, water, other inorganic biomass, and energy by microorganisms. Partial biodegradation can produce micro- to nano-sized fragments and other synthetic derivatives (UNEP, 2015).

Plastics produced from identical base polymers can exhibit remarkable variability in material characteristics and biodegradation rates due to differences in additives, manufacturing processes, and environmental exposure conditions. According to GESAMP (2015), biodegradable products of non-biological origin generally exhibit slow degradation patterns under natural environmental conditions and often require standard, industrial composting facilities to achieve complete breakdown. This assertion remains contentious, as the introduction of biodegradable plastics was originally intended to offer an environmentally sustainable alternative that minimizes long-term accumulation in natural ecosystems. Given the increasing prevalence of biodegradable plastics and the potential mismatch between product claims and environmental performance, evaluating their actual degradability in local environmental contexts is both timely and essential. The present study investigates the degradation behavior of three common biodegradable product categories: oxo-LDPE, compostable, and biodegradable under simulated laboratory conditions representative of realistic mismanaged waste accumulation sites, including freshwater systems, riverbanks, composting environments, and UV-exposed surfaces. The study also examines the influence of key environmental variables on the degradation process.

2. MATERIALS AND METHODS

2.1. Sample Selection and Preparation

The test materials included a commercially available garbage bag (GB) labelled as oxo-degradable, a lunch sheet (LS) labelled as compostable, and a salad plate (SP) labelled as biodegradable. Product selection was based on market availability, and samples were standardized by their date of manufacture to ensure comparability. Whatman No.42 filter papers (FP) served as the positive control due to their known biodegradability. Before testing, FP, SP, LS, and GB samples were cut into 0.61-0.66g, 1.10-1.50g, 2.10-2.60g, and 1.50-1.90g pieces, respectively. Samples were cleaned to remove surface contaminants, and the initial dry weights were measured using an analytical balance (OHAUS Pioneer). All experimental treatments were conducted in triplicate to ensure statistical reliability.

2.2. Exposure Media

Freshwater (FW), River Sediment (RS), Compost (COM), and UV exposures (UV) were simulating natural environmental conditions of a freshwater body, riverbank, landfill, and exposure to direct sunlight, respectively.

2.2.1. Experimental setups: Freshwater (FW), River Sediment (RS), and Compost (COM)

Two glass tanks, each of 60 × 30 × 30cm (L × W × H), were used to simulate freshwater (FW) and river sediment (RS) environments. The freshwater tank was filled with unfiltered water from a local lake and continuously aerated to mimic the littoral zone of a freshwater body. The river sediment tank was filled with moist sediment collected from a riverbank (GPS: 6º 56'57.9" N 79º 54'28.1" E) simulating benthic conditions. Test samples were individually enclosed in nylon mesh pockets to prevent loss of fragments during degradation, and then submerged in freshwater (FW) or embedded in river sediment (RS) (Fig. 1: a, b). The compost (COM) was prepared in a 100L transparent plastic container using layered additions of *Glyricidia sepium* leaves and other green manure, animal fertilizer, ready-made compost, and rock phosphate. The compost mixture was kept covered with intermittent aeration for four months to allow stabilization. Test samples were then placed in mesh pockets and embedded in the compost matrix (Fig.1: c). All experimental setups were maintained indoors near a window to expose samples to natural day–night light cycles for 12 months. Sampling was conducted monthly.

2.2.2. Experimental Setup: UV Exposure (UV)

To simulate natural sunlight, a sealed UV exposure chamber was constructed and equipped with UV lamps emitting light in the 280-320 nm range (~15W). The lamps were positioned 15 cm above the samples to ensure consistent irradiation intensity. Prepared samples were placed in 70 mL boiling tubes and subjected to continuous UV exposure for 8 months. Light intensity was monitored using a solar power meter (SM206), and samples were collected monthly for analysis (Fig.1: d).

Fig.1: Exposure media (a) Freshwater (b) River Sediment (c) Compost (d) UV chamber

2.3. Assessment of Physical Parameters Affecting Degradability

At each sampling, physicochemical parameters, i.e., pH and temperature, of FW, RS, and COM were recorded using a portable pH meter (APERA PH400S), and salinity was measured using a hand-held refractometer (ATAGO S/Mill-E).

2.4. Assessments of Mechanical Degradation

2.4.1. Assessment of Weight Changes

Samples exposed to FW, RS, and COM were withdrawn from the media, carefully cleaned, and the remaining dry weights were measured. Samples exposed to UV were directly weighed due to the absence of attached impurities of the medium. Fragmented samples were collected using a 200μm sieve. The Mean Weight Loss (MWL) was calculated using the equation below.

$$\text{Mean Weight Loss} = \frac{[(\text{Initial}_1 - \text{Final}_1) + (\text{Initial}_2 - \text{Final}_2) + (\text{Initial}_3 - \text{Final}_3)]}{\text{No. of replicates (3)}}$$

2.4.2. Assessment of the Loss of Mechanical Properties

The tensile strength of the initial and final samples was tested using a Universal testing machine (EKT 2001S), and the thickness of the samples was measured using a micrometer screw gauge. GB samples were cut into 75 × 15mm strips, and LS samples into 150 × 15mm strips, where the extension rate was 200mm/min at 25±2ºC (modified method from Kubik & Zeman, 2013). FP and SP samples were cut into 55 × 20mm strips, and the extension rate was 0.5mm/min at 25±2ºC (Artzi et al. 2016).

2.5. Assessment of Visual Changes During Degradation

Visual signs of degradation, including changes in shape, size, and color of initial and final test samples, were compared, and microscopic changes were analyzed via Scanning Electron Microscopy (SEM).

2.6. Assessment of Chemical Degradation

Initial and final test samples were scanned via Fourier Transform Infrared (FT-IR) spectroscopy in ATR mode at room temperature, covering 4000-400cm^{-1} wavelength to examine changes in the polymer structure during the experiment time. FT-IR spectra of initial samples were compared with the inbuilt library to confirm the significant polymer composition.

3. RESULTS AND DISCUSSION

According to UNEP (2015), if a product is marketed as biodegradable, a recognized standard such as EN 13432 (European), ASTM 6400 (USA), or ISO 17088 (international), which defines compostability, should be stated; however, none of the products contained such information available to the consumer.

3.1. Assessment of Weight Changes

In the freshwater exposure (FW) setup, the biodegradable salad plate (SP) exhibited the highest mean weight loss (MWL), ranging from 4.42% to 44.42%, relative to the positive control (FP). The maximum MWL observed for the oxo-degradable garbage bag (GB) was 6.82% over time (Fig. 2). Complete degradation was not observed for any test sample in FW; however, visual assessments indicated discoloration and slight deformation in samples. These findings are consistent with Kliem et al. (2020), who reported that aquatic environments typically support lower microbial activity due to the dilutive nature of water, limiting biodegradation. In contrast, in the river sediment (RS) and compost (COM) setups, SP underwent complete degradation within 120 days. GB exhibited minimal degradation in these media, with MWL values of 1.96% in RS and 1.16% in COM (Fig. 2). The enhanced degradation observed in RS and COM compared to FW is attributed to the higher microbial activity promoted by moist, oxygen-rich conditions in wet-sediment media, which favor aerobic microbial processes. These environments provided more favorable conditions for microbial colonization and the enzymatic breakdown of biodegradable materials.

Statistical analysis using one-way ANOVA and Kruskal–Wallis tests indicated significant differences (p=0.000; p<0.05) in MWL for FP, SP, and the compostable lunch sheet (LS) across the three environments, FW, RS, and COM. In contrast, MWLs for GB were not statistically significant (p=0.759; p>0.05), suggesting limited environmental degradation across all tested conditions.

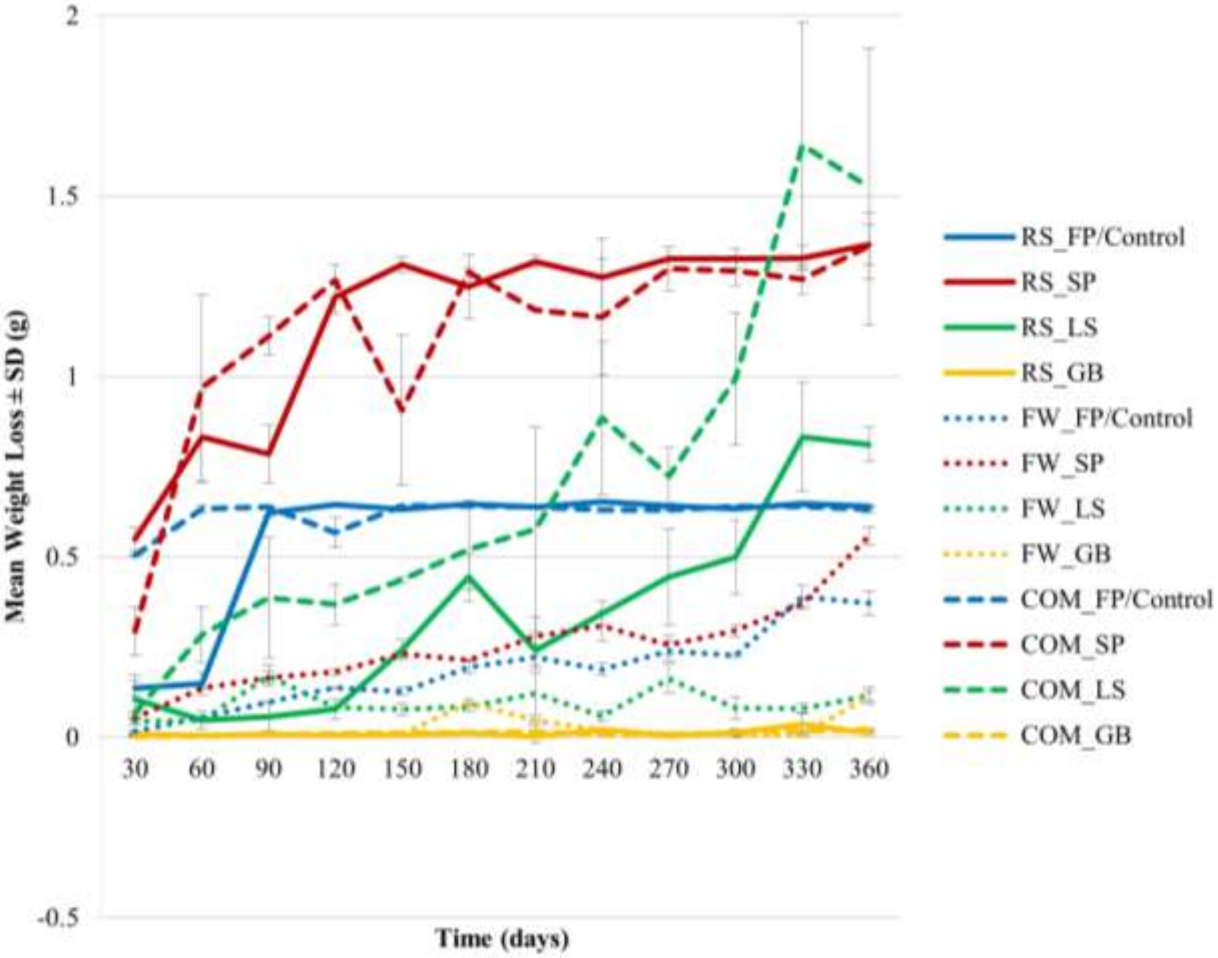

Fig.2: Mean weight loss ± SD of test samples in RS, FW, and COM during the experiment period

Under UV exposure, SP recorded a maximum MWL of 2.43%, indicating limited photodegradation (Fig. 3). Although GB exhibited slight increases in weight, likely due to moisture absorption, physical cracking and fragmentation were observed, indicating that photo-oxidative processes had initiated polymer breakdown.

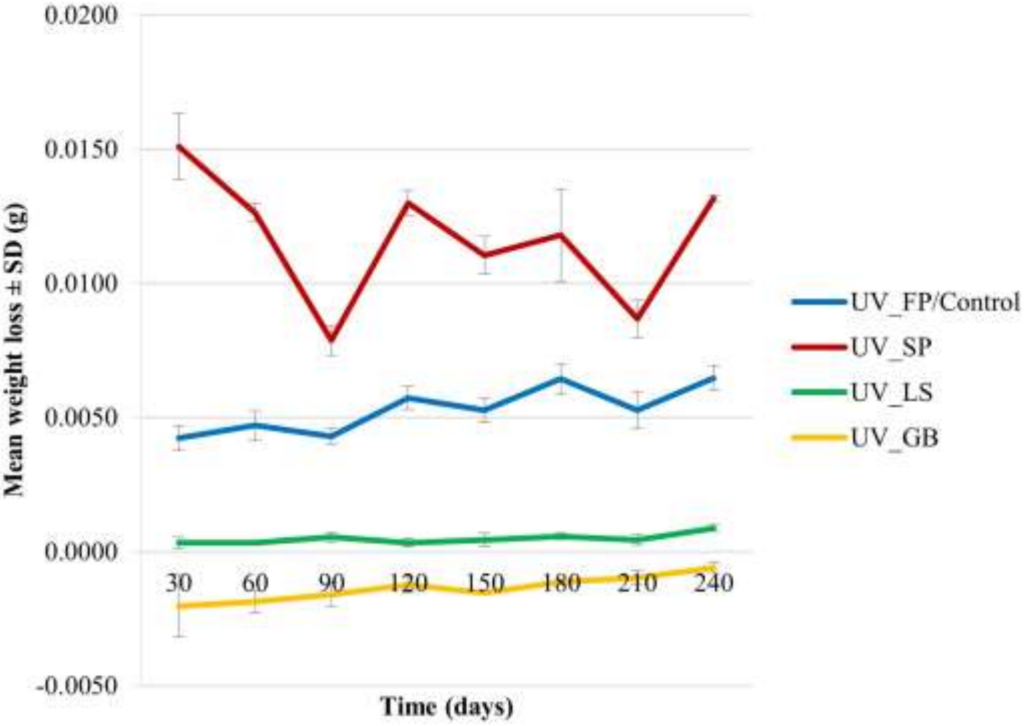

Fig.3: Mean weight loss ± SD of test samples under UV exposure during the experiment period

3.2. Assessment of the Loss of Mechanical Properties

The methodology for assessing the mechanical property degradation was adapted from Kubik & Zeman (2013) to account for the unexpected elasticity of the oxo-degradable garbage bag (GB) and the limited dimensions of test samples. A reduction in mechanical properties, specifically in tensile strength at break (F_b) and elongation at break (ε_b), is generally considered indicative of material degradation. However, in this study, GB samples exhibited increased mechanical performance over time in both river sediment (RS) and compost (COM) exposures. In RS, GB recorded a F_b of 7.25±0.29 N and ε_b of 317.78±9.15% while in COM, values were 4.35±0.88 N and 46.16±28.11%, respectively, suggesting a counterintuitive increase in elasticity potentially due to environmental plasticization or sample variability during early stages of degradation. In contrast, the biodegradable salad plate (SP) exhibited the lowest mechanical integrity under compost exposure, with a F_b of 26.72±2.77 N and ε_b of 0.57±0.22% indicating considerable material weakening. The compostable lunch sheet (LS) had the highest initial ε_b value (54.81±7.29%), suggesting a greater ability to undergo deformation without fracturing. However, LS samples became brittle across all exposure media by the first month of exposure, reflecting rapid degradation. All tested materials demonstrated a measurable decrease in thickness across the exposure period, further supporting progressive degradation (Table 1).

Table 1: Changes in Mean Tensile Strength at Break and Mean Elongation at Break of test samples in FW, RS, and COM media, compared to the initial. Samples in UV were omitted due to unavoidable size adjustments of the test samples.

Sample	Medium	Mean Thickness ± SD (mm)	Exposure time (months)	Mean Tensile strength at break (F_b) ± SD (N)	Mean elongation at break (ε_b) ± SD (%)	ΔFb (%)	Δεb (%)
SP	Initial	1.35 ± 0.01	0	248.35 ± 23.52	5.52 ± 0.30	-	-
	FW	0.54 ± 0.05	11	156.85 ± 4.96	4.50 ± 0.29	-36.84	-18.37
	RS	0.35 ± 0.05	1	52.17 ± 3.42	1.40 ± 0.08	-78.99	-74.57
	COM	0.62 ± 0.00	1	26.72 ± 2.77	0.57 ± 0.22	-89.24	-89.74
LS	Initial	0.01 ± 0.00	0	1.93 ± 0.06	54.81 ± 7.29	-	-
	FW			Too brittle to test at the first sampling			
	RS			Too brittle to test at the first sampling			
	COM			Too brittle to test at the first sampling			
GB	Initial	0.02 ± 0.00	0	3.87 ± 0.46	10.37 ± 1.15	-	-
	FW	0.02 ± 0.00	11	2.82 ± 0.67	9.53 ± 1.76	-27.16	-8.10
	RS	0.02 ± 0.00	11	7.25 ± 0.29	317.78 ± 9.15	87.50	2965.95
	COM	0.02 ± 0.00	11	4.35 ± 0.88	46.16 ± 28.11	12.5	345.34
FP/ Control	Initial	0.19 ± 0.00	0	25.85 ± 1.75	3.31 ± 0.40	-	-
	FW	0.15 ± 0.00	9	14.98 ± 2.37	1.45 ± 0.14	-42.07	-56.21
	RS	0.14 ± 0.01	1	0.63 ± 0.03	0.13 ± 0.00	-97.58	-96.12
	COM			Too brittle to test at the first sampling			

3.3. Assessment of Visual Changes During Degradation

Discoloration, deformation, loss of smoothness, fading, thinning, and weight loss of samples were observed as visual changes in RS, FW, and COM. SE micrographs revealed microscopic surface alterations, such as surface erosion, tiny cracks, pits, holes, and coagulated fibres formed during degradation. Fig.4 includes representative images comparing changes in the surfaces of LS samples in experimental media, highlighting the least changes under UV exposure.

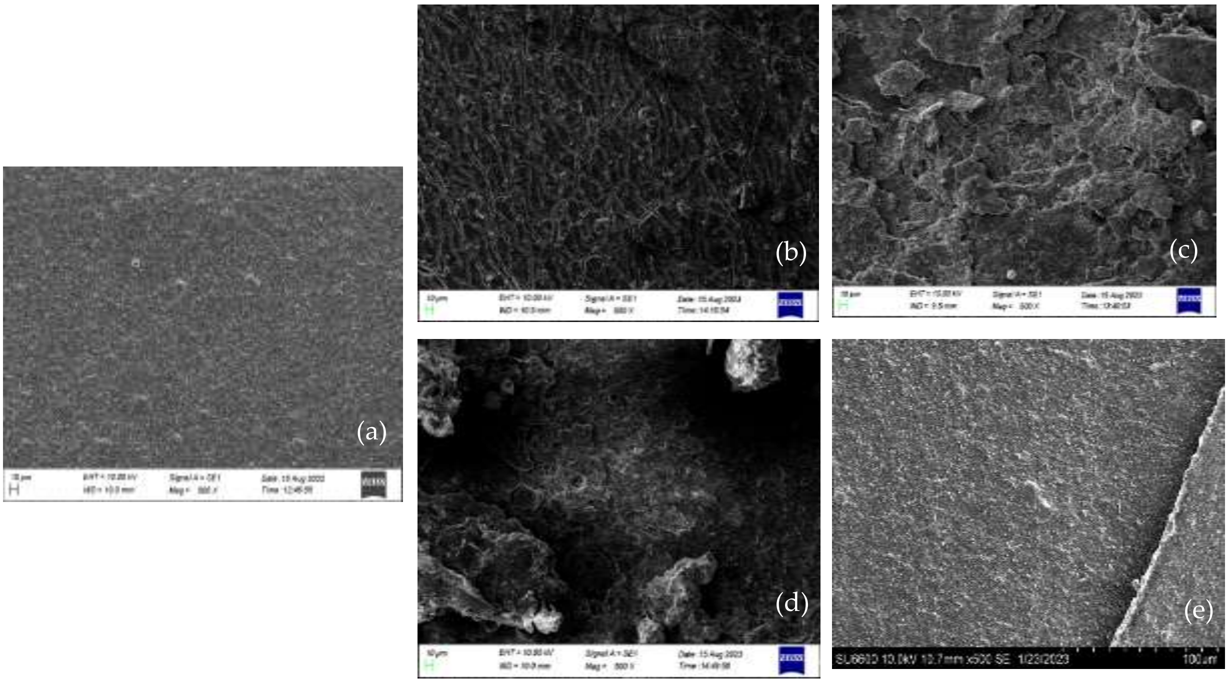

Fig.4: Microscopic changes on the surface topography of LS samples during the experiment period (500×) (a) Initial (b) in FW (c) in RS (d) in COM (e) in UV

3.4. Analysis of FT-IR Spectra (ATR Mode)

The change in chemical composition is considered one of the vital transformations in polymer degradation, resulting in environmentally friendly, simple compounds. According to the initial FT-IR spectra (ATR mode), the chemical composition of the biodegradable salad plate (SP) was matching to cellophane (~42%), the compostable lunch sheet (LS) was matching to polyester (~ 60%), the oxo-degradable garbage bag (GB) was matching to Low-Density Polyethylene (LDPE) (~ 63%), and the control, filter paper (FP) was matching to dextrose anhydrous (~ 32%). Apart from the chemicals revealed via FT-IR, the label of SP included natural sugarcane bagasse, a complex mixture he presence of

cornsta tton liners.

All SP samples in

the rive cellophane at

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(Fig.5).

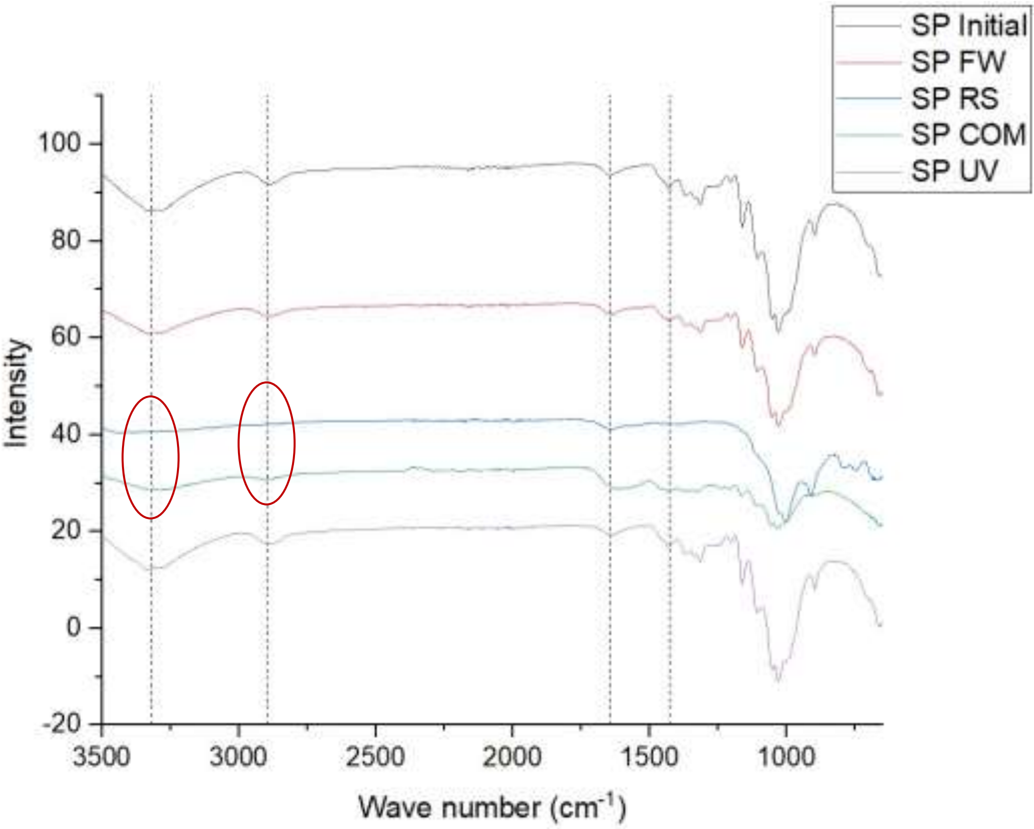

Fig.5: Initial FTIR vs final FTIR of SP samples under different exposures

The Final LS samples exposed to RS and COM revealed loss of characteristic peaks associated with polyester-derived components, specifically the C–O–C stretching vibrations at 1050–1150 cm^{-1} and C–H stretching vibrations at 2850–2950 cm^{-1}, indicating chemical degradation (Fig.6). In contrast, the final garbage bag (GB) samples did not exhibit notable changes in the characteristic LDPE spectral features. Peaks corresponding to C–H stretching (2850–2950 cm^{-1}), C–H bending (~1460 cm^{-1}), C–C stretching (1470–1500 cm^{-1}), and symmetric C–H stretching or in-plane C–C stretching (~720–730 cm^{-1}) remained intact, suggesting minimal or no polymer backbone breakdown (Ranjan & Goel, 2019). However, a new absorption peak emerged at ~1700cm^{-1} under UV exposure, indicative of carbonyl group (C=O) formation, marking photo-oxidative degradation (Ranjan & Goel, 2019) (Fig.7). Although GB was marketed as oxo-degradable, the final FT-IR spectra remained largely similar to initial profiles, reflecting incomplete biodegradation under all tested environmental conditions. This observation is consistent with previous findings that LDPE is inherently resistant to microbial degradation (Balasubramanian et al. 201 ol in biodegradability stud vior and eventually invite

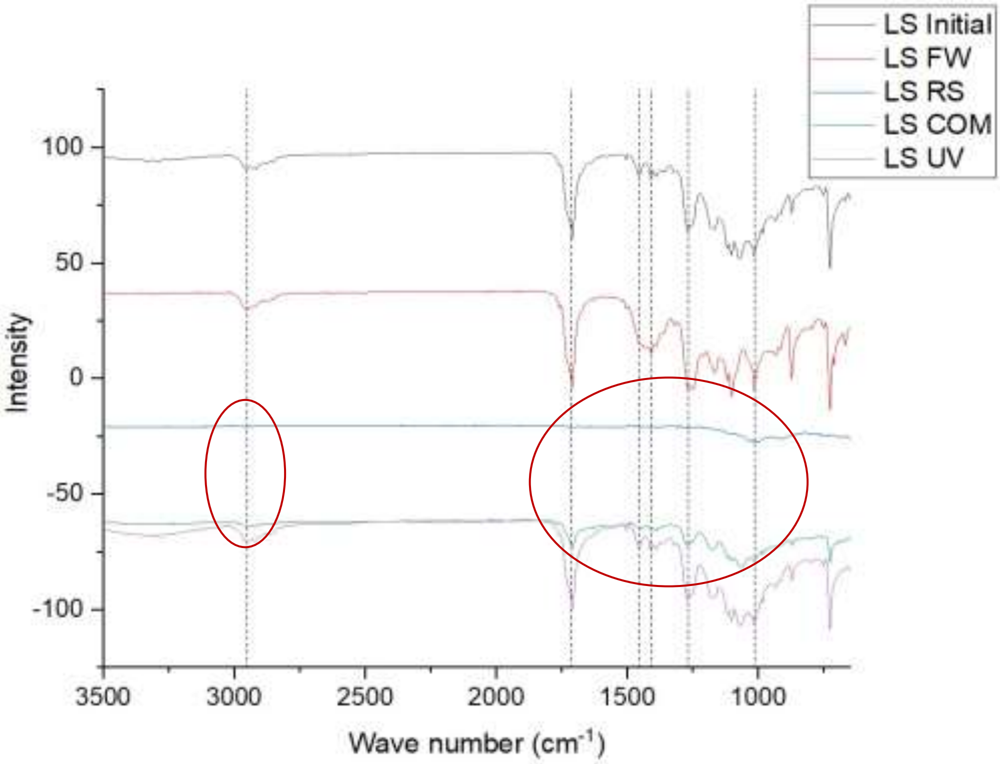

Fig.6: Initial FTIR vs final FTIR of LS samples under different exposures

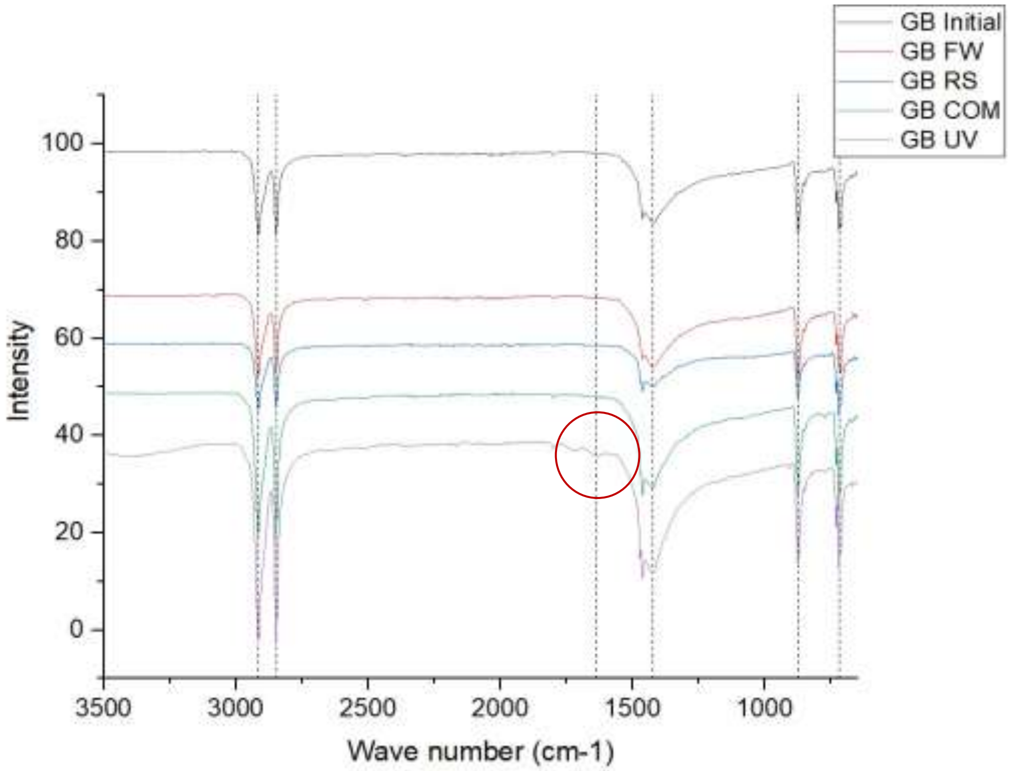

Fig.7: Initial FTIR vs final FTIR of GB samples under different exposures

3.5. Relationship Between Physicochemical Parameters and Mean Weight Loss (MWL)

The relationship between measured physicochemical parameters and mean weight loss (MWL) of test samples was analyzed using linear regression and locally estimated scatterplot smoothing (Loess) regression. In freshwater (FW), a statistically significant (p=0.003; p<0.05) negative correlation (R^2=60.2%) was observed between MW losses of garbage bag (GB) and pH in FW, where the pH ranged between 6.82-8.65, temperature 25.4-31.6 ºC, and salinity ~0 ppt. However, Loess Regression indicated a weaker non-linear relationship with the pH. In the compost (COM) medium, significant negative correlations were reported between MW losses and pH for both lunch sheet (LS) (p=0.044; p<0.05: R^2=44.80%) and garbage bag (GB) (p=0.021; p<0.05: R^2=53.23%) samples. Here, the pH ranged between 6.26-7.21, temperature 26.8-31.5 ºC, and salinity 0-5.6 ppt. Despite statistical significance, Loess regression suggested weak relationships overall, highlighting the complexity of environmental degradation dynamics. Given the limitations of periodic parameter measurements, continuous monitoring of physicochemical parameters is recommended in future studies to better elucidate their influence on polymer degradation.

4. CONCLUSIONS

The biodegradability of commercial polymer products under natural environmental conditions is highly dependent on both the chemical composition of the material and the characteristics of the exposure medium. This study demonstrated that degradation rates varied substantially across media types and sample materials. Sediment-rich environments (RS and COM) supported higher degradation of biodegradable polymers compared to fully aqueous conditions (FW), likely due to enhanced microbial activity and higher organic content. These findings suggest that waste accumulating in sediment-laden environments such as landfills and riverbanks may exhibit greater degradation potential than plastic waste suspended in water columns or exposed only to sunlight. The salad plate (SP) sample labelled as biodegradable showed complete degradation (100% MWL) within 120 days in both RS and COM conditions. The lunch sheet (LS), labelled compostable, recorded its highest MWL in COM after 330 days. In contrast, the garbage bag (GB), labelled oxo-LDPE/biodegradable, showed a maximum MWL of only 6.82% after 360 days. Although Whatman No. 42 filter paper (FP) was used as a positive control, its rapid disappearance across all media suggests that a more chemically stable negative control may be more appropriate for future studies. Nevertheless, the complete degradation of FP confirms that the environmental conditions in all test media were conducive to degradation processes. FT-IR analysis indicated chemical alterations in some samples, including the loss of characteristic polymer peaks, consistent with biological degradation. However, further research is needed to confirm whether the observed changes led to complete mineralization into non-toxic inorganic compounds.

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