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Microplastic pollution and risk assessment in selected beaches in Lagos State, Nigeria and degradation using associated microbial assemblages

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ABSTRACT

Microplastics are ubiquitous and a threat to global ecosystems causing serious environmental crisis. This study investigated the microbial assemblages associated with microplastics distributed in selected beaches in Lagos State, Nigeria. Sediment samples were aseptically collected, and bacterial species were isolated and identified. Bacteria isolated from the sediment area were screened for microplastic utilization and those with potential to degrade were selected for degradation studies. Degradation was quantified by weight loss (%). Surface morphology and structural changes were analysed using Scanning Electron Microscope (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) respectively. A total of 1846 items/kg of microplastics were extracted from all four beach sites. Fragments were the most prevalent (868 items/kg), and the least was pellets (221 items/kg). The most frequently observed microplastic colour was white (495 items). The Pollution Load Index (PLI) values ranged from 1.0 to 2.8. Bacteria isolated included *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Bacillus polymyxa*, *Alcaligenes faecalis*, *Micrococcus luteus*, *Staphylococcus aureus*, and *Proteus vulgaris*. For the 30-day degradation studies, Treatment A demonstrated the highest % weight loss (28.0%) for PET, while Treatment B recorded a weight loss of 20.0%. FTIR analysis confirmed biodegradation of PET and PP by both Treatments. SEM analysis revealed a compromised polymer matrix in the degraded microplastics, characterized by increased surface roughness, visible pits, cracks, and erosion patterns, all indicative of enzymatic or physical microbial activity. The study showed the potential of bacteria consortia from beach sediments to breakdown PET and PP, offering an environmentally friendly solution to address plastic contamination.

1. Introduction

Since the onset of industrialization in the 19th century, plastic pollution has become a widespread environmental concern, with plastic debris now reaching even the most remote parts of the planet [1,2]. Plastics are extensively used due to their durability, versatility, corrosion resistance, and affordability. However, these same properties render them highly persistent and resistant to degradation in the environment [3].

A significant portion of plastic waste in aquatic systems exists as microplastics (MPs), which are plastic particles less than 5 mm in size [4]. MPs may be intentionally manufactured (primary MPs) or result from the breakdown of larger plastics (secondary MPs) through UV exposure, mechanical forces, and microbial activity [5,6]. With plastic waste emissions projected to double by 2030 [7], the environmental threat posed by MPs is intensifying, especially in coastal and marine ecosystems. This is because oceans act as the final sink for land-based plastics, where fragmentation, persistence, high biological uptake, and

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pollutant adsorption cause microplastics to accumulate and exert long-term ecological and toxicological effects on marine food webs (Cole *et al.*, 2011).

Microplastics account for up to 80% of marine debris and are commonly derived from polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) [8–10]. Among these, PET and PP are of particular environmental relevance due to their extensive use in packaging, textiles, and consumer products. PET is a thermoplastic polyester composed of repeating units of ethylene glycol and terephthalic acid linked by ester bonds, forming a semi-crystalline aromatic polymer that is highly resistant to hydrolysis [11,12]. In contrast, PP is a polyolefin consisting of a saturated hydrocarbon backbone with methyl side groups, which confers high hydrophobicity, crystallinity, and resistance to enzymatic attack [3,13].

An estimated 4.8–12.7 million metric tons of plastic enter the oceans each year, with over five trillion plastic pieces currently floating in marine waters [14,15]. Despite efforts to clean visible litter, microplastics often remain in sandy beaches and sediments, making these environments important sinks and long-term reservoirs for MPs.

Beyond their physical presence, microplastics pose various risks as they can induce oxidative stress, inflammation, and cellular damage in aquatic organisms; they contain harmful additives such as plasticizers and flame retardants; and they act as vectors for pathogens, parasites, and persistent organic pollutants (POPs) such as phthalate esters [16–19].

Of particular concern is the “plastisphere”, a term describing the diverse microbial communities that colonize plastic surfaces in aquatic environments [20,21]. These communities may include bacteria, diatoms, ciliates, fungi, and potential pathogens such as *Vibrio* spp. The hydrophobic and roughened surfaces of plastics promote biofilm formation, which influences plastic buoyancy, aging, and degradation dynamics [22,23].

Recent studies have shown that certain plastisphere microorganisms possess the ability to degrade synthetic polymers. PET-degrading microorganisms such as *Ideonella sakaiensis*, *Thermobifida fusca*, *Bacillus subtilis*, *Pseudomonas putida*, and *Rhodococcus ruber* produce hydrolytic enzymes including PETase, MHETase, cutinases, and esterases that cleave the ester bonds of PET into mono-(2-hydroxyethyl) terephthalate (MHET), terephthalic acid, and ethylene glycol [24–26].

In contrast, the biodegradation of PP is considerably more recalcitrant due to the absence of hydrolysable functional groups. However, oxidative and co-metabolic degradation by bacteria such as *Bacillus*, *Pseudomonas*, *Rhodococcus*, *Streptomyces*, and *Aspergillus* species has been reported, involving enzymes such as alkane hydroxylases, laccases, manganese peroxidases, and monooxygenases that introduce carbonyl and hydroxyl groups, thereby initiating chain scission and surface erosion [27–29].

In Lagos State, Nigeria, several beaches serve as both recreational centres and ecological hotspots. Unfortunately, these areas face increasing plastic pollution due to poor waste management and urban runoff [30–32]. Despite existing global studies, there is a scarcity of localized data on microplastic abundance and the associated microbial communities in Nigerian coastal waters.

This study investigated the occurrence, abundance, and characteristics of microplastics in beach sediments from four selected beaches: Oniru, Alpha, Elegushi, and Eleko in Lagos State, Nigeria. The objectives were to assess the ecological risks posed by microplastics in the four study areas, to isolate bacterial assemblages associated with microplastics, and to evaluate their microplastic degradation potential. The research further aimed to determine the spatial distribution of microplastic pollution in the different beach sediments.

This study provides the first comprehensive characterization of microbial assemblages associated with microplastics from beaches in Lagos State, Nigeria, and demonstrates their ability to biodegrade common microplastic polymers (PET and PP) under laboratory conditions. Unlike most previous studies conducted in marine waters, this research focuses on coastal beach sediments in a tropical West African environment, an area previously underexplored for plastisphere studies. The combined use of culture-dependent methods, 16S rRNA gene sequencing, and advanced analytical tools (SEM and FTIR) to confirm both microbial colonization and structural polymer degradation offers a robust approach for linking microbial activity to plastic breakdown. The discovery that indigenous bacterial consortia can significantly degrade PET and PP highlights their biotechnological potential for eco-friendly bioremediation of plastic-contaminated coastal environments.

2. Materials and methods

2.1. Materials used in the study

The materials used for this study include:

Microplastics – Polypropylene (PP) and Polyethylene terephthalate (PET) (0.25 g each, particle size as specified), Nutrient Agar (Oxoid or equivalent- Ready Med RDM-NA-01), Bushnell Haas Medium (270 mL), Sodium Chloride (NaCl) (analytical grade-Molychem P.Code:18260), Hydrogen Peroxide (H_2O_2) (analytical grade- Central Drug House (p) Ltd. India), Sodium Dodecyl Sulphate (SDS) (analytical grade).

All reagents were of analytical grade and prepared using sterile distilled water unless otherwise stated.

2.2. Study area

This study was conducted in Lagos State, south-western Nigeria (Fig. 1), the country’s smallest state by land area (~365,861 ha; ~75,755 ha water) yet its economic hub, hosting over 11% of Nigeria’s population (~17 million) and renowned for its scenic coastal environments [33,34]. Samples were collected from four coastal beaches Alpha (N6.4225, E3.5236), Elegushi (N6.2518, E3.4432), Oniru (N6.4398, E3.4306) and Eleko (N6.4403, E3.8472) located within Eti-Osa, Victoria Island and the Lekki Peninsula, representing major recreational and ecological beach settings along the Lagos coastline [33–37].

Alpha Beach is a well-known public beach situated in Alpha Village within the Eti-Osa Local Government Area of Lagos State and lies at coordinates N6.4225, E3.5236 [38]. Bordered to the south by the Atlantic Ocean, the beach is accessible via the Igbefon axis of the Ajah-Epe Expressway. Positioned on the southern fringe of Victoria Island, Alpha Beach is recognized as a significant recreational and ecological destination in the region [33]. The Alpha Beach has a micro- to meso-tidal regime with semidiurnal tides (~1 m range at Lagos), which are typical of the Atlantic coast of Nigeria. There is steady wave action and moderate longshore transport due to the predominantly southwest-southwest winds. The wave heights typically range between 1 and 2 m, with more intense circumstances in the wet season [39]. The sediments in Alpha Beach are medium sized (mean ~1.1 Φ), indicating moderate energy conditions for sand mobilization and sorting by waves and currents. Medium sands indicate active reworking through backwash and swash procedures. In terms of mineralogy, Lagos beach sands are usually siliciclastic sediments dominated by quartz that originated in the Dahomey Basin and were altered by coastal processes [40].

Elegushi Beach is a private beach located in the Lekki area of Eti-Osa Local Government at coordinates N6.2518, E3.4432, the beach is owned and managed by the Elegushi royal family. Known for its luxury amenities, vibrant atmosphere, and stunning ocean views, Elegushi Beach has become a popular destination for leisure and entertainment, particularly among residents and tourists seeking an upscale coastal experience [34,35]. The Elegushi, like other Lagos beaches, experiences semidiurnal tidal changes and south-westerly winds, resulting in constant wave action and the seasonal variation with higher waves in rainy season, further contributing to dynamic swash zones [40]. Although there is less detailed documentation on the granulometry of Elegushi, Lagos barrier beaches are typically composed of medium to coarse

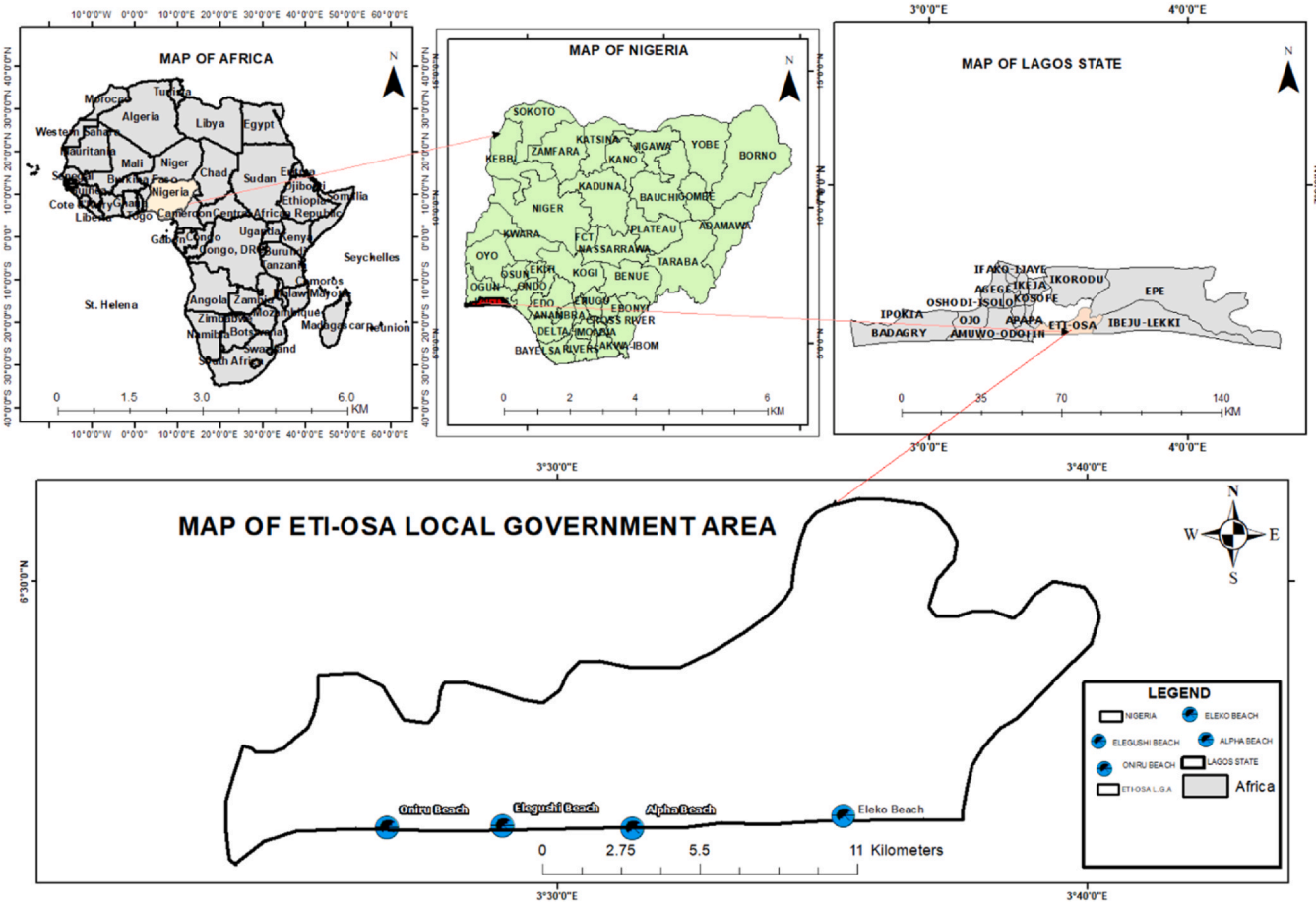

Fig. 1. Location of the study area in the Map of Lagos showing sample locations.

sands that are sorted by wave energy and dominated by quartz and other refractory minerals, with the presence of medium sand indicating a moderate to high-energy depositional environment with active wave sorting (Ogunleye *et al.,* 2019).

Oniru Beach is a private beach located in Victoria Island. It is situated at coordinates N6.4398, E3.4306 [36]. The beach of Oniru experiences the same semidiurnal tides and prevailing southwest winds as Elegushi Beach, resulting in wave activity that reworks the coastline sediments. Microplastic dispersion gradients shows how local hydrodynamics, such as wind-driven surface waves and alongshore currents, affect deposition and erosion. While specific grain-size data for Oniru Beach is not widely available, it is broadly similar to other Lagos beaches with sand-dominated sediments. Sorting and grain size reflect active wave processes typical of a moderate energy littoral zone. Mineralogy is expected to be quartz-rich, typical of Atlantic barrier sands [39].

Eleko Beach is a private beach located on the Lekki Peninsula, approximately 30 miles (about 48 kilometres) east of Lagos Island and 75 kilometres from the Lagos metropolis. Positioned at coordinates N6.4403, E3.8472, Eleko Community Beach is a typical sand barrier-lagoon coastal village [36]. The beach fronts the Atlantic Ocean and is known for its serene environment, cleanliness, and exclusivity. Revered as one of the most well-maintained beaches along the Lekki-Epe Expressway, Eleko Beach attracts numerous tourists seeking a quiet, organized, and scenic coastal experience [37].

Eleko Beach, experiences the same semi-diurnal tidal range and south-westerly wave climate. When exposed to open Atlantic fetch, the energetic conditions can be comparatively stronger, particularly during periods of heavy wind and waves [39]. The sediments of Eleko Beach are coarser (~0.56 Φ) than Alpha, indicating higher energy deposition from stronger waves that deposit coarser sand. This demonstrates active wave sorting and dynamic nearshore processes. Quartz and other hard minerals dominate the composition of this beach, as they do on other beaches in the region [40]. Fig. 1 shows the location of the study area showing the sample locations.

2.3. Sample collection

As described by Auta et al. [41] with a few modifications, sediment samples were collected at 0–4 cm depth from three different points (Points A, B, and C) at low tides with a quadrat of 0.5 m x 0.5 m placed 2 m apart from high tide in undisturbed areas. The samples collected were transported to the laboratory and stored at −20°C for further analysis. All samples were collected in triplicates.

2.4. Extraction of microplastics

All sediment samples were weighed (2 kg) and dried at 60 °C in an oven for 48 h. The dried samples were sieved and 500 g of each sample was weighed in a glass beaker and mixed with fully saturated 30% w/w NaCl solution with density of 1.2 g/mL in a conical flask, stirred for 2 min and kept undisturbed overnight for denser particles to settle down [42] as shown in Fig. 2 below. The supernatant was mixed with 30% H_2O_2 with Fe (II) solution Fenton's reagent at 250 rpm and temperature not exceeding 70 °C. This process was repeated until no organic matter was seen in the container [43]. The digested mixture was then subjected to vacuum filtration and filtered through a nitrocellulose membrane of pore size 0.45 μm [44]. The MP particles collected on the membrane were dried for 24 h at ambient room temperature [45].

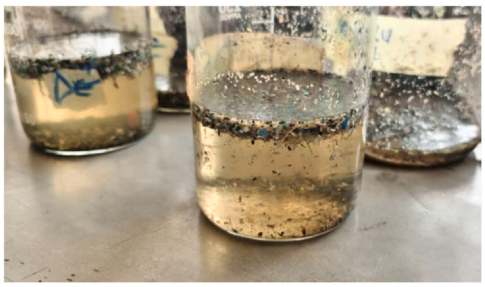

Fig. 2. Microplastics floating in beaker during extraction process.

2.5. Identification and characterization of microplastics

Visible microplastics that floated were collected and also, those on the membrane were visually sorted and counted. The dried membrane was observed under a stereo zoom microscope to fetch a count of smaller microplastics at 300X magnification. The colour, size, and shape were visually estimated in order to categorise them based on physical attributes. Microplastics in sediment samples were measured as particles per kg dry sediment [46].

2.6. Microplastics risk assessment

The Pollution Load Index (PLI) is a standardised tool used to monitor and compare pollution levels across different sampling sites. It is used in environmental monitoring and pollution assessment (Table 1). The parameters permit the visualization of the contribution of microplastic pollution at each sampling point incorporates the Contamination Factor (CF), calculated as the ratio of the microplastic concentration (Ci) at a specific site to the background value (Coi), which represents the lowest microplastic concentration recorded within the study area. The PLI was calculated using the Eqs. (1) and (2)

$$\text{Containation Factor(CF)} = \frac{C_i}{C_0} \quad (1)$$

$$\textit{Pollution Load Index } (PLI) = \sqrt[n]{CF_1 \times CF_{ii}.....CF_n} \quad (2)$$

Where:

n = number of pollutants (Microplastics shapes) per location

2.7. Preparation of microplastics

Polypropylene and polyethylene terephthalate plastics were washed thoroughly with distilled water to remove surface contaminants. The plastics were then treated with 70% ethanol for 30 min for surface sterilization and air-dried under sterile conditions. To remove organic impurities, the microplastics were soaked in 30% hydrogen peroxide for 24 h at room temperature. After oxidation treatment, the particles were rinsed multiple times with sterile distilled water and air-dried at 103 °C for 48 h. To enhance surface hydrophilicity and promote microbial attachment, the plastics were further treated with 2% sodium dodecyl sulphate (SDS) for 2 h, followed by repeated washing with sterile distilled water to remove residual surfactant. The treated plastics were irradiated for 2 days under ultra violet rays and stored in sterile containers until use. Each experimental flask received 0.25 g of prepared microplastic.

Table 1
The Hazard Level Criteria for Microplastic Pollution.

Risk Category	PLI	CF	Risk Category
I	< 10	CF < 1	Minor
II	10–20	1 < CF < 3	Medium
III	20–30	3 < CF < 6	High
IV	> 30	CF > 6	Danger

Han et al., [47]

2.8. Bacteria isolation and identification

Bacteria were isolated from sediments and microplastics collected in the study area. One gram of each sediment sample was mixed with 9 mL of 0.9% normal saline to prepare a stock solution, followed by ten-fold serial dilutions up to 10^{-6}, as described by Auta [48], and Rana and Rana [49]. From appropriate dilutions, 0.1 mL was plated onto sterile nutrient agar and spread evenly. Plates were incubated at 37°C for 24 h. The colonies that developed were sub cultured to obtain pure colonies and subjected to preliminary biochemical tests, and molecular confirmation using the 16 s rRNA sequencing technique.

2.8.1. Confirmation of isolated bacteria

Polymerase Chain Reaction (PCR) was done for the respective samples after the isolation of genomic DNA. Universal primers 16S rRNA (5'-AAACTC/ TAAAG/TGAATTGACGG-3') and (5'-ACGGGCGGG TGTGTA/GC- 3') was used. The PCR product was analysed on 1% agarose gel and purified using gel extraction kit (Fermentas, USA). M13 forward and reverse primers were used to sequence the rRNA amplified products in a Genetic Analyzer. The National Centre for Biotechnology Information BLAST database was used to amplify nucleotide sequence. These sequences were aligned with selected genera representative members by using CLUSTAL W program [50].

2.8.2. Quantification of isolated bacteria DNA

After isolation and confirmation, the genomic DNA were quantified at 260 nm using UV-1280 Spectrophotometer using water as blank. Liquid media was inoculated with bacterial colonies and kept in shaker at 37 °C for overnight. After 16 h, 1 mL culture from overnight media was taken and put in 50 mL media flask. The flasks were then kept in a shaker and readings were taken after every two hours [50].

2.9. Screening of isolates for biodegradation studies

Bacteria isolates were screened for their ability to degrade microplastics. Each isolate was inoculated into Bushnell Haas (BH) medium containing (per litre): 0.20 g $MgSO_4$, 0.02 g $CaCl_2$, 1.0 g KH_2PO_4, 1.0 g K_2HPO_4, 1.0 g NH_4NO_3, and 0.05 g $FeCl_3$. The medium was supplemented with 0.4 g of microplastics and incubated at room temperature for 4 weeks. Control sets (media + microplastic but without bacteria) were maintained in parallel. All experiments were conducted in triplicate ([41], 2018). *Proteus* sp., *B. polymyxa*, *B. subtilis, A. faecalis and Pseudomonas* sp. recorded the highest growth and from the biodegradation screening were therefore selected for the biodegradation studies.

2.10. Biodegradation studies

Isolated potential microplastic-degrading bacteria were cultured on freshly prepared nutrient agar at 33 °C for 24 h. These were then inoculated into nutrient broth and incubated in a rotary shaker at 29 °C, 150 rpm, until reaching the stationary phase. Individual isolates and Treatments (combination of selected strains) were prepared by pooling equal volumes of the cultures at the same physiological stage to form the inoculum for biodegradation experiments [48].

In the biodegradation experiment, 10% of the prepared bacterial cultures were inoculated into 270 mL of Bushnell Haas (BH) medium contained in Erlenmeyer flasks, each supplemented with 0.25 g of sterilized polypropylene (PP) and polyethylene terephthalate (PET) microplastics as the sole carbon source. Uninoculated BH broth containing microplastics was used as the control and maintained under identical conditions. The flasks were incubated at 35 °C on a rotary shaker at 150 rpm for 40 days. Optical density (OD), pH, and microbial

Table 2
Physicochemical Properties of Beach Sediment.

Parameters	Oniru Beach	Alpha Beach	Eleko Beach	Eleghusi Beach
Ph	9.01 ± 0.01	9.01 ± 0.06	9.09 ± 0.01	9.08 ± 0.02
Temperature (°C)	22.75 ± 0.25	23.40 ± 0.20	24.00 ± 0.20	23.90 ± 0.30
Nitrogen(mg/kg)	22.63 ± 0.13	23.01 ± 3.63	21.32 ± 0.69	20.01 ± 0.63
Moisture (%)	12.22 ± 0.31	12.94 ± 2.09	14.03 ± 0.48	14.76 ± 0.26
Salinity (ppt)	0.08 ± 0.00	0.14 ± 0.05	0.19 ± 0.00	0.19 ± 0.00
Organic matter (%)	1.78 ± 0.03	1.39 ± 0.68	1.32 ± 0.24	0.90 ± 0.19

Values are presented as mean ± standard error of mean (SEM) of three replicates.

counts were measured at 10-day intervals throughout the incubation period. All experiments were conducted in triplicate ([41], 2018).

2.11. Determination of dry weight of the residual microplastics

The percentage weight loss of microplastics was determined after 30 days of incubation on a rotary shaker at 150 rpm and 35 °C. After incubation, the residual microplastics were recovered and treated with 2% (w/v) aqueous sodium dodecyl sulphate (SDS) to remove attached microbial biofilms and residual medium components. The mixture was incubated in a shaker at 120 rpm for 4 h. Subsequently, the samples were rinsed thoroughly with distilled water, placed on filter paper, and dried overnight at 60 °C. The dried residual microplastics were then weighed, and the percentage weight loss was calculated using Eq. (3) as described by Nademo et al. [51].

$$\text{Weight Loss}(\%) = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \text{X100} \quad (3)$$

2.11.1. Determination of rate constant

As described by Auta [48], the data was processed to determine the rate constant of microplastic reduction by using the first-order kinetic model based on the initial and final weights along specific intervals (10 days) using Eq. (4).

$$\text{Rate Constant} K = -\frac{1}{t}\left(In\frac{W}{Wo}\right) \quad (4)$$

where K is the first-order rate constant for microplastic uptake per day; t is time in days; W is the weight of residual microplastics (g); and W_O is the initial weight of PP microplastics (g).

The half-life, which is defined as the time it will take for the amount of the microplastics to be reduced by half its initial size, was calculated using Eq. (5) below;

$$Half\ life \quad (t_{1/2}) = \frac{In2}{k} \quad (5)$$

2.12. Fourier transform infrared (FTIR) analysis

Structural changes on the surface of the residual microplastics were analysed using a Fourier Transform Infrared (FT-IR) spectroscopy. The FT-IR analysis was employed to detect alterations in functional groups, indicating possible biodegradation of the polymer structure. Spectra were recorded in the range of 450–4000 cm^{-1} for all low-density polyethylene (LDPE) samples [51].

2.13. Scanning Electron Microscopy (SEM)

The surface morphology of residual microplastics were analysed using scanning electron microscopy (SEM) after the degradation study to assess structural changes resulting from bacterial activity. Prior to SEM analysis, the film was washed thoroughly with 2% (w/v) aqueous sodium dodecyl sulphate (SDS) and rinsed repeatedly with distilled water under gentle shaking to remove microbial residues. The cleaned film was then flushed with 70% ethanol to enhance surface exposure for visualization. A piece of the air-dried film was mounted on a sample holder, coated using a master coater, and examined under a high-resolution scanning electron microscope [51].

2.14. Statistical analysis

All experiments were carried out in triplicates and analyses of data were performed using IBM SPSS software (version 23) with analysis of variance. The value of $p < 0.05$ was considered statistically significant.

3. Results and discussion

This study was conducted in Lagos State located in the south western region of Nigeria. Although it is the smallest state by land mass, covering approximately 365,861 ha of which 75,755 ha are water Lagos is considered the economic and industrial hub of the country. it accounts for over 11% of Nigeria's total population with an estimated population of 17 million. The state is renowned for its rich tourism potential, particularly its coastal regions, which have been regarded as some of the most scenic riverine areas in the country [33,34]. Samples were collected from four beaches (Alpha, Elegushi, Oniru and Eleko Beach) within Lagos State, in South-West Nigeria.

3.1. Physicochemical properties of beach Sediment

There was no significant difference in the physicochemical parameters across the beach sediment (Table 2). The pH levels across all four beaches were consistently alkaline, ranging from 9.01 ± 0.01 at Oniru and Alpha Beaches to slightly higher values of 9.09 ± 0.01 at Eleko Beach and 9.08 ± 0.02 at Eleghusi Beach. Temperature measurements showed some variation between the beaches. Oniru Beach recorded the lowest sediment temperature at 22.75 ± 0.25 °C, while Eleko Beach had the highest at 24.00 ± 0.20 °C. Nitrogen content in the sediment varied slightly among the beaches. Alpha Beach had the highest average nitrogen concentration at 23.01 ± 3.63 mg/kg followed by Oniru Beach (22.63 ± 0.13 mg/kg), Eleko Beach (21.32 ± 0.69 mg/kg) and Eleghusi Beach (20.01 ± 0.63 mg/kg). Moisture content in the beach sediment ranged from 12.22 ± 0.31% to 14.76 ± 0.26%. Salinity levels ranged from 0.08 ± 0.00–0.19 ± 0.00 ppt. Organic matter content in the sediment was highest at Oniru Beach (1.78 ± 0.03%), followed by Alpha Beach (1.39 ± 0.68%), Eleko Beach (1.32 ± 0.24%) and Eleghusi Beach (0.90 ± 0.19%).

Physicochemical properties such as pH, temperature, moisture content, salinity, nitrogen, and organic matter shaping beach ecosystems, influencing microbial activity, and affecting the degradation of pollutants like microplastics [52–55]. Across all four beaches, sediments were consistently alkaline. Alkaline conditions can promote microbial colonization, biofilm formation, and chemical breakdown of microplastics [56]. Neutral to slightly alkaline pH is generally favourable for microbial diversity [57]. The observed alkalinity may result from carbonate minerals, seawater intrusion, or anthropogenic input [58–60].

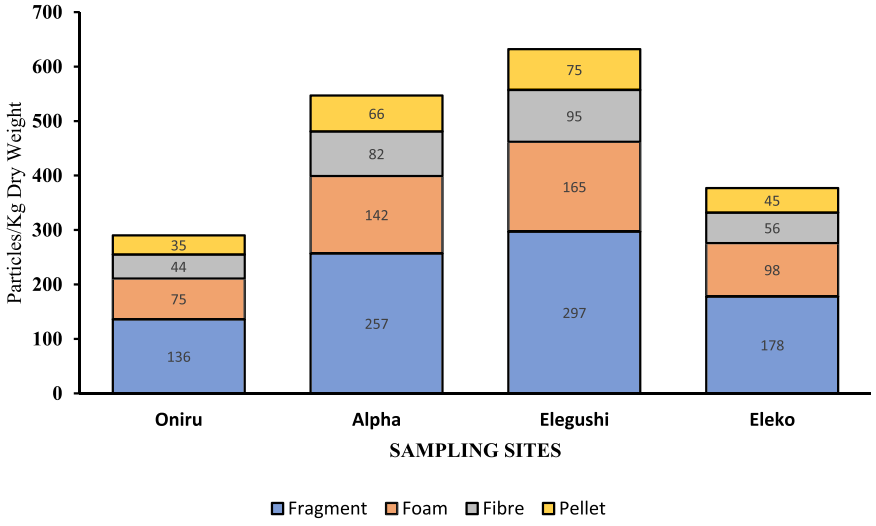

Fig. 3. Abundance and distribution of different types of microplastics across the sampled beach locations.

Sediment temperature showed minor variation among beaches, potentially influenced by sun exposure, sampling time, and beach orientation. Warmer temperatures tend to accelerate microbial metabolism and chemical reactions [61,62]. Nitrogen levels varied slightly, reflecting differences in nutrient input and microbial activity. Higher nitrogen supports more active microbial communities, enhancing organic matter decomposition and microplastic degradation [63,64]. Moisture content also varied without significant differences among beaches. Adequate moisture facilitates microbial growth, while extremely dry conditions hinder microbial activity [65]. Factors like sediment texture and tidal influence affect moisture levels. Salinity levels were consistently low, typical of tidal beach environments where seawater flushing prevents salt accumulation [66]. This uniformity suggests limited freshwater input and consistent marine influence [58,67]. Organic matter content varied, with higher levels at Oniru Beach, likely due to anthropogenic activity or natural debris deposition. Organic matter supports microbial life and can promote microplastic degradation [68,69].

3.2. Abundance and distribution of microplastics in beach sediments

A total of 1846 items/kg dry weight of microplastics were recovered from sediment samples across the four sampling sites (Fig. 3.). The microplastic abundance varied among the beaches, with Elegushi Beach recording the highest count (632 items/kg), followed by Alpha Beach (547 items/kg), Eleko Beach (377 items/kg), and Oniru Beach (290 items/kg). The higher microplastic load observed at Elegushi and Alpha Beaches can be attributed to intense anthropogenic activities, including tourism, coastal trading, and proximity to urban drainage discharges. In contrast, Eleko and Oniru, which are less commercially active, exhibited comparatively lower abundance. These spatial patterns align with reports by Ilechukwu et al. [36] and Akindele et al. [70], who found that microplastic concentrations along Nigerian beaches increase with population density and waste generation intensity.

Among the microplastic types, fragments were the most abundant (868 items/kg dry weight), followed by foams (480 items/kg), fibres (277 items/kg), and pellets (221 items/kg). The dominance of fragments suggests that secondary microplastics, derived from the weathering and mechanical breakdown of larger plastic debris, are the major contributors to beach microplastic loads. Similar findings have been reported by Auta et al. [41] and Browne et al. [71] in tropical and temperate coastal environments, respectively. The high occurrence of foams is indicative of widespread use and poor disposal of expanded polystyrene (EPS) materials, such as food trays and packaging products, which are lightweight and easily transported by wind and water currents. The occurrence of fibres, although relatively lower, implies input from synthetic textiles and fishing activities, consistent with observations by Naji et al. [72] and Hidalgo-Ruz et al. [73], who reported similar fibre sources in coastal sediments Persian Gulf, Iran.

The colour distribution of the recovered microplastics (Fig. 4.) revealed a predominance of white particles (495 items), followed by brown (411), black (374), and blue (269). Less frequent colours included yellow (136), green (85), and red (77). The dominance of white and brown microplastics suggests extensive photodegradation and oxidation of parent plastics, resulting in pigment fading and discolouration over time [13]. This pattern mirrors the findings of Auta et al. [41] who reported similar colour dominance in tropical marine sediments, indicating prolonged exposure to sunlight and physical abrasion in Malaysia. The prevalence of light-coloured particles also increases their ingestion potential by marine organisms, as they are often mistaken for natural food particles such as zooplankton [74].

The total microplastic abundance recorded in Lagos beaches (1846 items/kg dry weight) is considerably higher than values reported for Moroccan Mediterranean beaches. Azaaouaj et al. [75] reported 40–230 items/kg along the eastern Moroccan Mediterranean coast, while Azaaouaj et al. [76], found an average of approximately 59 items/kg on the northwestern coast. Even the lowest Lagos site (290 items/kg) exceeds the highest Moroccan values, indicating substantially greater microplastic contamination, likely due to intense urbanization, tourism, and inadequate waste management. Similarly, Buoninsegni et al. [77] reported high microplastic presence along the Ferrara Coast (Italy), particularly small microplastics (2402 items/m^2). Although units differ (items/kg vs items/m^2), both studies highlight heavy contamination in urbanized coastlines and dominance of secondary microplastics. Overall, Lagos beaches exhibit higher sediment microplastic burdens compared to Moroccan sites and are comparable to heavily impacted European coasts, underscoring strong anthropogenic influence. In terms of composition, Lagos beaches were dominated by fragments, whereas Moroccan beaches reported fibres as the predominant type. This difference may reflect variation in dominant pollution sources: textile-derived inputs and fishing activities along the Mediterranean coast versus extensive breakdown of macroplastic litter in Lagos. Nonetheless, all three regions demonstrate patterns typical of anthropogenically influenced coastlines, where secondary microplastics dominate and spatial variability correlates with human activity intensity.

Overall, the abundance and composition trends in this study are consistent with global patterns, emphasizing that fragments and foams dominate in high-activity beach environments. The total abundance (1846 items/kg) exceeds previously reported values for Lagos beaches (1230 items/kg; [70]) and is comparable to findings from Malaysia (1560 items/kg; [78]), indicating a high local input of mismanaged

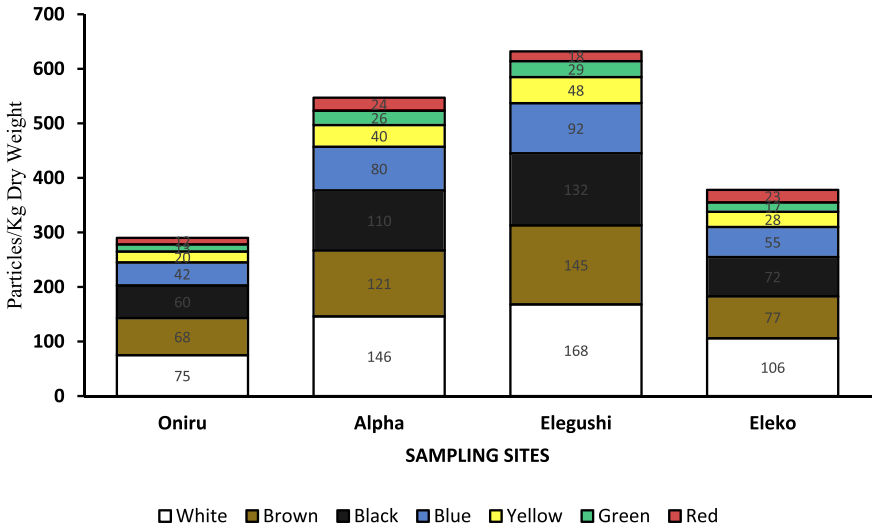

Fig. 4. Abundance and distribution of different colours of microplastics across the sampled beach locations.

plastic waste. These results underscore the growing environmental burden of microplastics in Nigeria's coastal zones and highlight the need for improved waste management, enforcement of plastic use regulations, and public awareness initiatives to mitigate future accumulation.

The total microplastic abundance recorded in this study (1846 items/kg dry weight) is higher than values previously reported for Lagos coastal sediments and many other Nigerian coastal environments, indicating an increasing trend in plastic contamination. For instance, Akindele et al. [70] reported 1230 items/kg in sediments from selected Lagos beaches, while Ilechukwu et al. [36] recorded lower concentrations along less urbanized stretches of the Nigerian coastline. The higher values obtained in the present study, particularly at Elegushi (632 items/kg) and Alpha (547 items/kg) Beaches, are likely linked to intense anthropogenic pressure such as tourism, coastal trading, urban runoff, and proximity to drainage channels. Similar relationships between human activity intensity and microplastic abundance have been documented globally, where beaches close to densely populated and industrialized areas consistently show elevated microplastic loads [71,73].

When compared with international studies, the total abundance observed here is comparable to values reported from other tropical coastal regions, such as Malaysian beaches (1560 items/kg; [41]) and parts of the Persian Gulf [72], but higher than many temperate beach sediments, which often range between 100 and 1000 items/kg [71,73]. This suggests that tropical urban coastlines, characterized by rapid population growth, inadequate waste management, and high plastic consumption, may act as hotspots for microplastic accumulation.

The dominance of fragments in the present study is consistent with numerous reports from both Nigerian and global coastal sediments [70,71,78]. Fragments are typically classified as secondary microplastics, formed through photodegradation, mechanical abrasion, and thermal oxidation of larger plastic items such as bottles, bags, and packaging materials [13]. Their prevalence indicates long-term environmental weathering and continuous input of macroplastic debris that subsequently breaks down in situ. The substantial proportion of foam particles further reflects the widespread use of expanded polystyrene (EPS) for food packaging and insulation in coastal urban centers, a pattern also reported in tropical sediments by Auta et al. [41].

Fibres, although less abundant than fragments and foams, are commonly reported in coastal sediments worldwide and are generally associated with domestic wastewater, laundering of synthetic textiles, and degradation of fishing nets and ropes [72,73]. The presence of pellets, though lowest in abundance, suggests contributions from industrial raw materials and spillage during transportation and handling, as similarly observed by Browne et al. [71].

The colour distribution, dominated by white, brown, and black particles, is also in agreement with previous studies in Nigerian and other tropical marine environments [78] Light-coloured and faded plastics are typically indicative of prolonged exposure to ultraviolet radiation and oxidative weathering, which leads to pigment loss and surface embrittlement [13]. Such weathered particles are of particular ecological concern, as their resemblance to natural food items such as zooplankton and detritus increases the likelihood of ingestion by benthic and pelagic organisms [74].

Overall, the abundance, composition, and spatial distribution patterns observed in this study are consistent with both regional and global reports, but the comparatively higher total concentration suggests an escalating local input of mismanaged plastic waste. This aligns with trends reported for rapidly urbanizing coastal zones in developing countries, where ineffective waste collection, open dumping, and direct discharge into drainage systems contribute significantly to marine plastic pollution [36,70,78]. These findings underscore the urgent need for improved solid waste management, stricter enforcement of plastic-use regulations, and sustained public awareness campaigns to mitigate further accumulation of microplastics in Nigeria's coastal sediments.

Also, compared to previous studies, the recorded levels are lower. Walenna et al. [79] recorded higher MPs levels in various land uses, with agricultural soils reaching 64 particles/g, and Olarinmoye et al. [46] reported 310–2319 particles/kg in lagoon sediments bordering Lagos while Ilechukwu et al. [36] recorded higher MP abundance in Lagos beaches, with up to 170 items/50 g at Eleko. These elevated levels have been linked to poor waste management, plastic migration, and litter fragmentation due to photochemical and mechanical processes [36].

3.3. Microplastic risk assessment (pollution load index- PLI)

Table 3 estimates the PLI values of the different sample locations with Elegushi having the highest PLI score of 2.17, indicating that the

Table 3
Risk category of microplastic pollution across the four beach locations.

Locations	PLI	Risk Category
Elgushi Beach	2.17	Highly Polluted (about twice the baseline)
Alfa Beach	1.88	Polluted (above baseline but less than site 1)
Eleko Beach	1.23	Slightly Polluted
lOniru Beah	1	At baseline (no excess pollution)

site is experiencing pollution above the baseline level, and that the contamination is considered moderate to high. It also indicates that the microplastic load concentration in the beach sediment in Elegushi is about 2.17 times higher than the natural or reference condition.

The pollution load index (PLI) for the four polluted investigated beach sites ranged from 1.00 to 2.17, indicating spatial variability in microplastic contamination levels. Elegushi Beach recorded the highest PLI value (2.17), representing a 117% increase above baseline conditions, and therefore signifying the most severe microplastic contamination among the 4 beach sites. Alfa Beach exhibited a PLI of 1.88 (88% above baseline), suggesting substantial pollution but at lower magnitude than Elegushi Beach site. Eleko, with a PLI of 1.23 (23% above baseline), can be classified as slightly polluted, while Oniru Beach, with 1.00, reflects conditions equivalent to the reference baseline and is therefore, considered unpolluted.

According to Baycan et al. [80] a PLI value of > 1 denotes pollution, whereas values ≤ 1 indicates unpolluted conditions. Based on this threshold, three out of the four beach sites assessed can be classified as polluted with varying degrees of severity, with contamination hotspots clearly identified at Elegushi and Alfa beach. Such elevated microplastic loads in these locations may be linked to anthropogenic activities such as tourism, fishing activities, plastic waste runoff, coastal urbanisation, inadequate waste management, and hydrodynamic processes that promote debris deposition. Ecologically, it demonstrates an increased risk to bottom dwelling organisms that may ingest microplastics with possible entry into the local food web.

The spatial pattern observed suggest that targeted management interventions, particularly at the most polluted sites, may be necessary to mitigate further microplastic accumulation in coastal sediments. Additionally, long-term monitoring is recommended to evaluate the effectiveness of any remediation strategies and to detect potential seasonal or inter annual trends in contamination levels.

The elevated microplastic loads observed at these sites may be linked to intensified anthropogenic pressures, including tourism activities, coastal urbanisation, inadequate solid waste management, and hydrodynamic processes favouring the deposition of buoyant polymer particles. This spatial distribution pattern underscores the need for targeted pollution control strategies at the most contaminated sites to prevent further accumulation of microplatics in coastal sediments. Furthermore, continuous monitoring is essential to assess the efficiency of mitigation measures and to detect potential seasonal or interannual variation in microplastic contamination trends.

Additionally, the observed higher values recorded in Elgushi beach and Alfa indicate that ecological risks may be exacerbated when water flow is reduced as the experiment (sample collection) was carried out during the dry season this was in conformity with the work reported by Baycan et al. [80]. Where samples were collected during the wet and dry seasons indicating that the ecological risk of microplastics increased during the dry season as the water flow is reduced and vice vasa. Microplastics (MPs), defined as plastic particles < 5 mm in size [81], have become widespread contaminants in terrestrial and marine environments, posing significant ecological and health risks. Their presence in beach sediments reflects anthropogenic activity and land-sea interactions. A total of 1847 particles/kg (dry weight) was recorded, with fragments being the most prevalent, site-specific abundance was highest at Elegushi Beach (632 items/kg) likely due to intensive tourism and urban runoff. The relatively lower count at Oniru, a private beach, may be attributed to stricter plastic use restrictions [38].

3.4. Enumeration and identification of bacterial species in beach sediment

No significant difference was observed in the total bacterial counts across the four beach sites (Fig. 5). Elegushi Beach recorded the highest level with an average of 10.6 ± 7.91 x 10^4 CFU/g. This was followed by Oniru Beach (6.1 ± 2.19 x 10^4 CFU/g), Eleko Beach (4.2 ± 1.73 x 10^4 CFU/g), and Alpha Beach, which had the lowest count

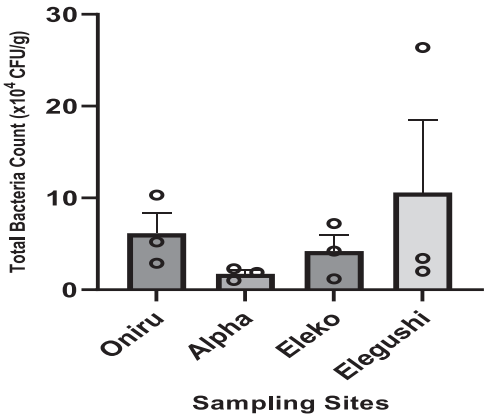

Fig. 5. Total bacterial count of Beach sediment. Values are presented as mean ± standard error of mean (SEM) of three replicates.

(1.7 ± 0.38 x 10^4 CFU/g). The mean total bacterial count across all sites was 5.65 ± 20.40 x 10^4 CFU/g. A total of eleven distinct bacterial species were isolated from the sediment samples. These include: *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Micrococcus luteus*, *Serratia marcescens*, *Alcaligenes faecalis*, *Bacillus mycoides*, *Bacillus polymyxa*, *Bacillus cereus*, *Bacillus subtilis*, *Staphylococcus epidermidis*, and *Proteus vulgaris*.

Beach sediments provide a dynamic habitat for diverse microbial communities, many of which possess significant bioremediation potential [82]. These microorganisms evolved metabolic pathways and enzyme systems that enable the breakdown of complex environmental pollutants, including synthetic polymers. Their presence in polluted sites suggests an ability to utilize such contaminants as carbon and energy sources [83]. They also often exhibit significant resistance to toxic compounds, increasing their relevance in bioremediation processes.

In this study, there was no significant difference in total bacterial count across the sampling sites, with mean total bacterial count ranging from 1.7 ± 0.38 × 104 in Alpha Beach to 10.6 ± 7.91 × 104 CFU/g in Elegushi Beach. Variations in bacterial load across the sites can be linked to environmental factors such as organic matter content, salinity, moisture, sediment texture, and anthropogenic input [84]. The elevated bacterial count observed at Elegushi Beach may be attributed to increased human activity and pollution load.

These relatively high bacterial counts indicate a strong potential for natural attenuation and microbial degradation of plastics in these beach sediments. Previous studies have reported comparable or higher bacterial densities depending on sampling depth, season, and pollution gradients. Soffritti et al. [85] reported bacterial counts ranging from 1.1 × 103–1.6 × 105 CFU/g in beach sands of the North Adriatic Sea, Italy. Suzuki et al. [86] documented counts between 2.8 × 103 and 1.7 × 107 CFU/100 g in Kizaki Beach, Japan. Similarly, Udofia et al. [87] recorded counts of 2.1 × 106–3.6 × 106 CFU/g in sediments of the Iko River Estuary, Nigeria, while Odewumi and Quist [88] recorded 1.45 × 104–12.4 × 104 CFU/g in Araromi Beach, Nigeria.

As mention above the isolated species are commonly associated with organic matter degradation, nutrient cycling, and plastic biodegradation in environmental matrices.

The bacterial genera isolated in this study are consistent with those reported in other studies on coastal and sediment ecosystems. Udofia et al. [87], Odewumi and Quist [88], and Soffritti et al. [85] reported isolating and identifying *Escherichia coli*, *Proteus*, *Streptococcus*, *Staphylococcus*, *Klebsiella*, *Clostridium*, and *Actinomycetes*. These microbial populations are shaped by sediment characteristics and nutrient availability, which influence both their abundance and functional capacity [89].

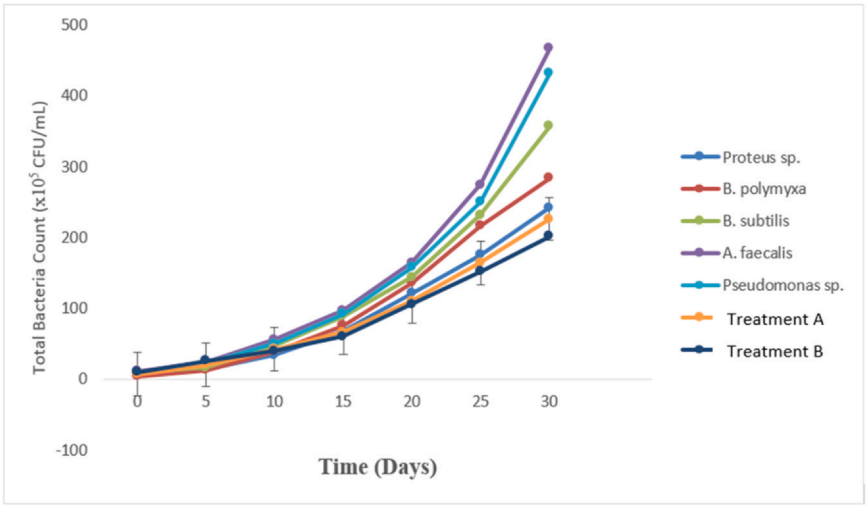

Fig. 6. Growth of Bacterial Isolates during 30-day PET biodegradation.

3.5. Bacteria growth during the biodegradation study period of PET

Figure Six (Fig. 6). illustrates the growth patterns of individual bacterial isolates (*Proteus sp.*, *Pseudomonas sp.*, *Bacillus polymyxa*, *Bacillus subtilis*, *Alcaligenes faecalis*) and two bacterial consortia (Treatments A and B) over a 30-day incubation period, expressed as total bacterial count ($\times 10^5$ CFU/mL). At the start (day 0), all bacterial populations showed relatively low counts, indicating the adaptation or lag phase. A gradual increase in growth was observed from day 5 to day 20 across all isolates and Treatments corresponding to the exponential phase of bacterial proliferation. Beyond day 20, a steeper rise in cell density occurred, showing enhanced microbial activity and utilization of available microplastic substrates.

By day 30, *A. faecalis* exhibited the highest bacterial count (467×10^5 CFU/mL), followed closely by *Pseudomonas sp.* (432×10^5 CFU/mL) and *B. subtilis* (357×10^5 CFU/mL). *B. polymyxa* and *Proteus sp.* displayed moderate growth levels, while the mixed cultures (Treatments A and B) showed comparatively lower but steady increases, reaching about $202–226 \times 10^5$ CFU/mL at the end of the incubation period.

Overall, the graph demonstrates that all isolates were capable of sustained growth over time, with *A. faecalis* and *Proteus sp.* showing superior proliferation potential. The Treatments, although exhibiting slower growth, maintained stable population increases, suggesting possible interspecies interactions that moderate overall growth dynamics.

The progressive increase in bacterial counts over the 30-day period indicates that all isolates and consortia were able to adapt and actively utilize the available substrate, suggesting their potential role in biodegradation. The superior growth of *A. faecalis* and *Proteus sp.* implies a higher metabolic efficiency and possibly stronger enzymatic capacity for substrate breakdown. The moderate yet steady growth of *B. polymyxa*, *B. subtilis*, and *Pseudomonas sp.* reflects stable adaptation and sustained activity throughout the incubation period. Although the mixed consortia (Treatments A and B) exhibited lower growth rates compared to individual isolates, their consistent increase suggests synergistic interactions that could enhance overall degradation performance through complementary metabolic pathways. These results highlight the potential of both individual strains and microbial consortia in biodegradation processes under extended incubation conditions.

3.6. Biodegradation of PET microplastics (Weight Loss)

In terms of degradation efficiency, Treatment A exhibited the highest percentage weight loss, with a 28.0% reduction in the initial PET weight. This was followed by *Bacillus subtilis*, *Pseudomonas* sp. and Treatment B, which individually caused a 20.0% weight reduction. *Bacillus polymyxa* and *Alcaligenes faecalis* followed, with 16.0% and 12.0% weight loss, respectively, while *Proteus* sp. recorded the lowest PET weight loss at 8.0% (Fig. 7).

Treatment A achieved the highest PET reduction (24.0%), indicating possible synergistic action. *B. subtilis* and *Pseudomonas* sp. each caused 16.0% weight loss, while *A. faecalis*, despite high growth, only achieved 8.0%, suggesting its metabolism may target other substrates. This highlights that high bacterial growth does not always equate to high degradation efficiency.

Numerous studies have identified PET-degrading microbes, with *Bacillus* among the most common, often expressing PETase [90]. Compared to the present study, lower degradation rates were reported by Guo et al. [91] (4.28% in 5 weeks using *Rhodococcus pyridinivorans* P23) and Liu et al. [92] (1.8–16.2% over two months using deep-sea bacterial consortia). Key genera included *Alcanivorax*, *Pseudomonas*, *Thalassospira*, and *Nocardioides*. Biodegradation efficiency varies with microbial species, enzyme production, environmental factors, and intermicrobial interactions [93,94].

3.7. Rate constant and half life of PET after biodegradation studies

Table 4 presents the removal constants (K) and half-lives ($t½$) for microplastic degradation by the various bacterial isolates and treatments. The removal constant (K) indicates the rate of microplastic degradation (day^{-1}), while the half-life represents the time required for 50% of the microplastics to degrade.

The control sample showed no degradation (K = 0.0), confirming that abiotic degradation was negligible under the experimental conditions. Among the pure isolates, *Bacillus subtilis* and *Pseudomonas sp.* demonstrated the highest removal constants (K = 0.0066 day^{-1}) with corresponding shortest half-lives (105 days), indicating strong microplastic-degrading potential. *B. polymyxa* followed with K = 0.0051 day^{-1} and a half-life of 136 days, while *A. faecalis* (K = 0.00384 day^{-1}; $t½$ = 180 days) and *Proteus sp.* (K = 0.0024 day^{-1}; $t½$ = 289 days) showed relatively slower degradation rates.

The consortia treatments showed enhanced degradation efficiency compared to individual isolates. Treatment A recorded the highest degradation rate (K = 0.00972 day^{-1}) and shortest half-life (71 days), suggesting synergistic interactions among the bacterial members that facilitated faster breakdown of microplastics. Treatment B also performed well (K = 0.0066 day^{-1}; $t½$ = 105 days), comparable to *B. subtilis* and *Pseudomonas sp.*

These findings are consistent with earlier reports identifying *Bacillus* and *Pseudomonas* species as effective plastic degraders. Auta [48]

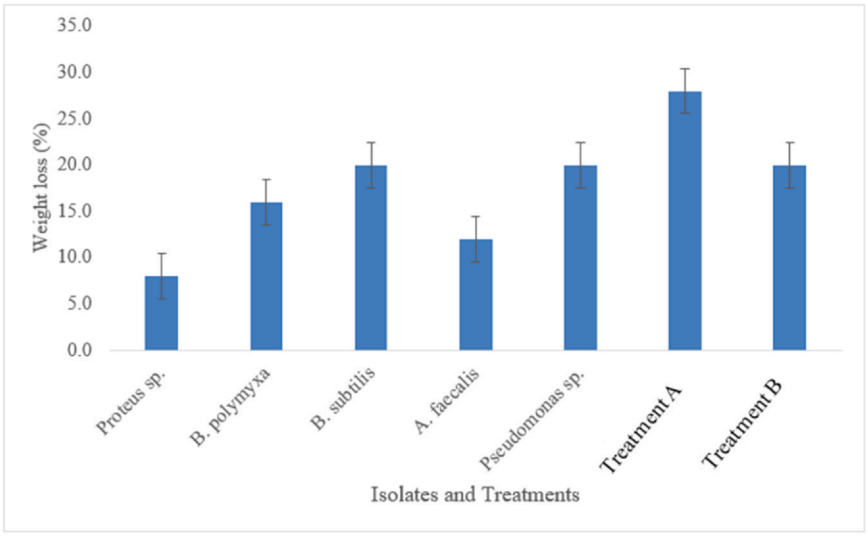

Fig. 7. Percentage weight loss of polyethylene terephthalate (PET) after 30 days Biodegradation.

Table 4
Rate Constant and Half-life of polyethylene terephthalate (PET) after 30 days biodegradation studies.

Isolate	Initial Weight (g)	Final Weight (g)	Removal Constant (K) day-1	Half-Life (Days)
Control	0.25	0.25	0.0	-
Proteus sp.	0.25	0.23	0.0024	289
B. polymyxa	0.25	0.21	0.0051	136
B. subtilis	0.25	0.20	0.0066	105
A. faecalis	0.25	0.22	0.00384	180
Pseudomonas sp.	0.25	0.20	0.0066	105
Treatment A	0.25	0.18	0.00972	71
Treatment B	0.25	0.20	0.0066	105

demonstrated that isolates of *Pseudomonas* and *Bacillus* obtained from aquatic environments effectively degraded polyethylene and polypropylene films, attributing their performance to oxidative and hydrolytic enzyme secretion such as laccases, esterases, and monooxygenases. Similarly, Hooda and Mondal [95] reported that *Bacillus subtilis* achieved significant polyethylene degradation with a half-life of approximately 100–120 days, comparable to the 105 days recorded in this study.

While *Proteus sp.* and *A. faecalis* showed slower degradation rates, their activity corroborates the work of Harshvardhan and Jha [96], who observed gradual but steady plastic deterioration by *Proteus sp.* under similar conditions. The superior performance of the mixed consortia aligns with reports by Ojeda *et al.* (2011) and Yang et al. [97], which demonstrated that microbial consortia outperform single strains due to synergistic metabolic interactions, enzyme complementation, and enhanced biofilm formation on polymer surfaces.

Overall, these results emphasize the advantage of employing microbial consortia over single isolates in plastic biodegradation studies. The high degradation rate observed in Treatment A highlights the potential of mixed bacterial systems as promising candidates for the bioremediation of microplastic-polluted environments.

3.8. Growth pattern of isolates during 30-day PP biodegradation

The growth patterns of five bacterial isolates (*Proteus sp.*, *Pseudomonas sp.*, *Bacillus polymyxa*, *Bacillus subtilis*, and *Alcaligenes faecalis*) and two bacterial consortia (Treatments A and B) during a 30-day incubation period of PP microplastics is presented in Fig. 8. Growth was measured as total bacterial count ($\times 10^5$ CFU/mL).

At day 0, all bacterial isolates and consortia exhibited low cell densities, indicating the adaptation or lag phase. Between days 5 and 20, a gradual rise in bacterial counts was observed across all samples,

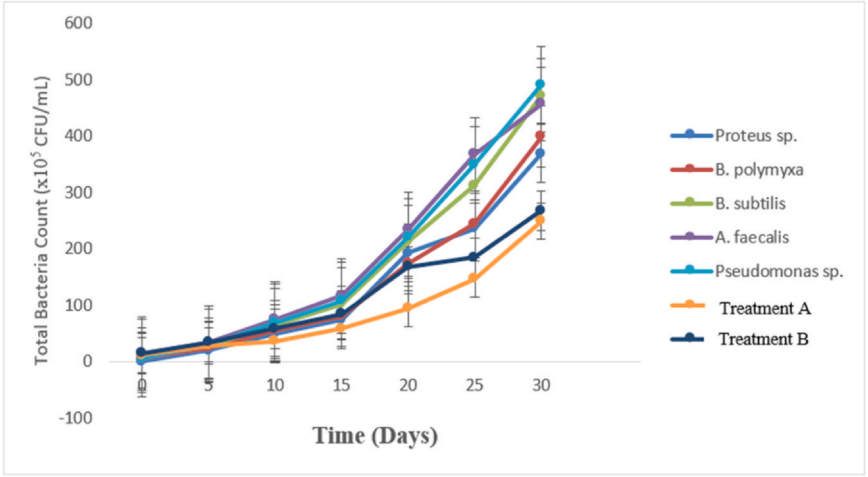

Fig. 8. Growth of Bacterial Isolates during 30-day PP biodegradation studies.

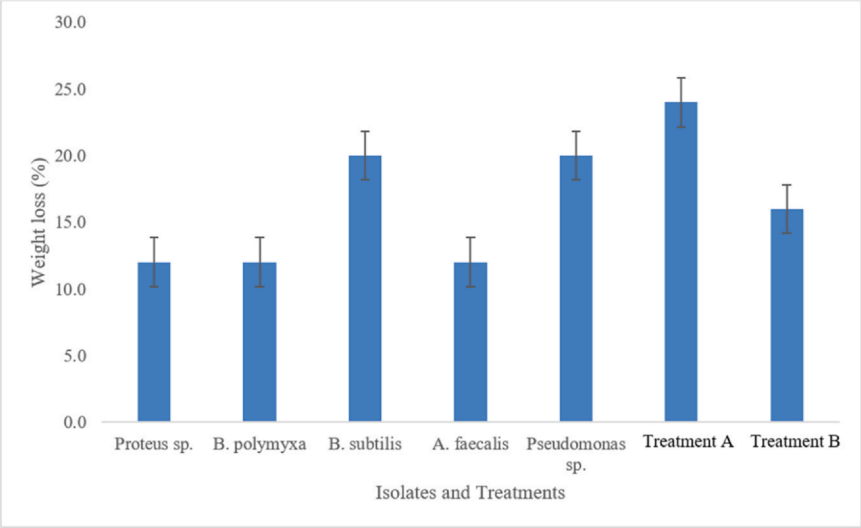

Fig. 9. Percentage weight loss of polypropylene (PP) after 30 days biodegradation.

showing active cell multiplication and substrate utilization. After day 20, the bacterial populations entered a more rapid growth phase, with pronounced increases in total counts by day 30. By the end of the incubation period, *Pseudomonas sp.* showed the highest bacterial count (491 $\times 10^5$ CFU/mL), followed closely by *A. faecalis* (472 $\times 10^5$ CFU/mL) and *B. subtilis* (457 $\times 10^5$ CFU/mL). *B. polymyxa* and *Proteus sp.* recorded moderate growth, while the mixed cultures (Treatments A and B) exhibited relatively lower but consistent increases, reaching 249 and 268 $\times 10^5$ CFU/mL, respectively, by day 30.

Overall, the graph indicates that all isolates and consortia were capable of sustained growth over the study period, with *Pseudomonas sp.* and *A. faecalis* demonstrating the highest proliferation potential. The steady growth trends of the consortia suggest stable microbial adaptation and possible cooperative interactions that support substrate utilization.

The progressive increase in bacterial counts over the 30-day incubation period indicates effective adaptation and active colonization of the plastic substrate by all isolates and Treatments. The pronounced growth observed in *Pseudomonas sp.* and *A. faecalis* suggests a higher enzymatic capability and stronger affinity for plastic surfaces, possibly due to efficient secretion of extracellular enzymes involved in polymer breakdown. The steady growth of *B. subtilis*, *B. polymyxa*, and *Proteus sp.* reflects consistent metabolic activity and biofilm development, which are essential for initiating plastic degradation. Although the mixed consortia (Treatments A and B) exhibited comparatively lower cell densities, their stable and sustained growth implies synergistic interactions that may enhance collective biodegradation efficiency through complementary metabolic pathways. Overall, these results demonstrate that both individual bacterial isolates and consortia possess the potential to participate in biofilm-mediated degradation of plastic materials under prolonged incubation.

3.9. Biodegradation of polypropylene (PP)

Treatment A exhibited the highest %weight loss recording a 24.0% reduction in the initial PP weight. This was followed by *Bacillus subtilis* and *Pseudomonas* sp. individually both recording 20.0% weight reduction each. Treatment B recorded 16.0% reduction in PP weight while *Proteus* sp., *Bacillus polymyxa*, and *Alcaligenes faecalis* all recorded 12.0% reduction in PP weight (Fig. 9).

Polypropylene (PP) is a widely used synthetic polymer valued for its durability, chemical resistance, and versatility [98,99]. Commonly found in packaging, automotive parts, textiles, and household items, its resistance to degradation has contributed significantly to environmental pollution [100]. Microbial biodegradation offers a promising solution by harnessing microorganisms to break down PP without harsh chemicals or harmful by-products.

Table 5
Rate Constant and Half-life of polypropylene (PP)) after 30 days biodegradation studies.

Isolate	Initial Weight (g)	Final Weight (g)	Removal Constant (K) day-1	Half-Life (Days)
Control	0.25	0.25	0.0	-
Proteus sp.	0.25	0.22	0.0038	180
B. polymyxa	0.25	0.22	0.0038	180
B. subtilis	0.25	0.20	0.0066	105
A. faecalis	0.25	0.22	0.0038	180
Pseudomonas sp.	0.25	0.20	0.0066	105
Treatment A	0.25	0.19	0.0082	84
Treatment B	0.25	0.21	0.0051	135

Weight loss analysis revealed Treatment A achieved the highest PP degradation (20.0%), suggesting synergistic enzyme activity. *B. subtilis* and *Pseudomonas sp.* followed with 16.0% each, consistent with their growth and known degradation roles. Treatment B recorded 12.0%, possibly limited by antagonistic interactions or poor synergy. Biodegradation efficiency varied due to factors such as enzymatic activity, interspecies interactions, and metabolic adaptation. Similar variability is noted in other studies. Jeon et al. [101] reported 4% PP degradation by *Lysinibacillus sp.* after 26 days, while Wichatham et al. [102] recorded 17.52% weight reduction by *Streptomyces ardesiacus* under lab conditions.

3.10. Rate constant and half-life of polypropylene (PP)

The removal rate constants (K) and half-lives (t½) for microplastic degradation by bacterial isolates and consortia are presented in Table 5. The control sample showed no measurable degradation (K = 0.0 day^{-1}), confirming that abiotic factors such as photolysis and hydrolysis did not significantly contribute under the experimental conditions. Among the individual isolates, *Bacillus subtilis* and *Pseudomonas sp.* recorded the highest removal constants (K = 0.0066 day^{-1}) and shortest half-lives (105 days), indicating strong enzymatic potential and high biodegradation efficiency. Moderate degradation rates were observed for *Proteus sp.*, *Bacillus polymyxa* and *Aerococcus faecalis* (K = 0.0038 day^{-1}; t½ = 180 days), suggesting comparatively slower degradation kinetics.

Enhanced degradation performance was observed in the bacterial

consortia compared to the single isolates. Treatment A exhibited the highest degradation rate (K = 0.0082 day^{-1}) and the shortest half-life (84 days), indicating synergistic interactions among the constituent bacterial species that enhanced polymer breakdown. Treatment B (K = 0.0051 day^{-1}; t½ = 135 days) also performed well, surpassing most of the individual isolates but remaining slightly less efficient than Treatment A. The superior performance of the consortium can be attributed to metabolic cooperation, complementary enzyme activity, and efficient colonization of polymer surfaces leading to faster oxidation and hydrolysis of polymer chains.

These findings are consistent with previous reports highlighting the degradation capabilities of *Bacillus* and *Pseudomonas* species. Auta [48] demonstrated that *Pseudomonas* and *Bacillus* isolates from aquatic environments effectively degraded polyethylene and polypropylene films, achieving comparable degradation rates (K ≈ 0.006–0.007 day^{-1}). Hooda and Mondal [95] similarly reported that *Bacillus subtilis* degraded polyethylene with a half-life of approximately 110 days, closely matching the 105 days observed in this study. Conversely, *Proteus sp.* and *Aerococcus faecalis* exhibited lower degradation rates, consistent with findings by Harshvardhan and Jha [96], who observed limited polymer deterioration by these species even after extended incubation.

The enhanced degradation observed in microbial consortia aligns with previous studies showing that mixed microbial cultures out-perform single strains due to synergistic interactions and enzyme complementarity. Ojeda *et al.* (2011) and Yang et al. [97] reported that microbial consortia enhanced polymer degradation through cooperative metabolism, enzyme diversity, and biofilm formation on polymer surfaces, resulting in faster breakdown of polymer chains. The shorter half-life recorded in Treatment A supports this assertion, demonstrating the benefit of using mixed microbial communities in bioremediation applications.

Generally, the results confirm that *B. subtilis* and *Pseudomonas sp.* are among the most efficient single degraders of microplastics, while the consortia, particularly Treatment A, exhibited superior degradation efficiency. These findings underscore the potential of microbial consortia as sustainable biological tools for the remediation of microplastic-contaminated environments.

The biodegradation study in Tables 3 and 4 demonstrates that certain bacteria can effectively degrade polypropylene, though with varying efficiencies. Treatment A holds promise for bioremediation strategies, given its higher rate constant and shorter half-life, while others are weak degraders of PP and PET. Their enzymatic systems likely have low activity or affinity for PP and PET degradation. The control experiment confirms that there is no biological breakdown without microbial action.

In conclusion, The 30-day degradation experiment revealed substantial mass loss for both polymers, with PET exhibiting a higher weight reduction (28.0%) under Treatment A, while PP showed a lower but still considerable loss of 20.0% under Treatment B. Weight loss is a widely used indicator of polymer deterioration and reflects surface erosion, chain scission, and the formation of low-molecular-weight fragments resulting from abiotic and/or biotic degradation processes [13]. The pronounced mass loss observed in the present study suggests that the applied treatments created conditions highly favorable for polymer breakdown, as further supported by FTIR spectral changes indicating the formation of oxygen-containing functional groups associated with oxidative and hydrolytic degradation.

For PET, the recorded 28% weight loss after 30 days is markedly higher than values reported for natural weathering and mild laboratory exposures. Napper and Thompson [103] documented only 6–12% mass loss for PET films after 30 days of UV-accelerated aging in seawater, while Gewert et al. [104] reported approximately 5–15% surface erosion during short-term marine exposure. In contrast, the magnitude of weight loss observed in the present study is comparable to that reported under biologically or enzymatically enhanced conditions. Yoshida et al. [25] demonstrated that PET incubated with *Ideonella sakaiensis* underwent up to 25–30% mass reduction within one month due to enzymatic hydrolysis of ester linkages. Similarly, Ronkvist et al. [105] reported 20–35% weight loss of PET films during cutinase-mediated degradation. These comparisons indicate that the 28% mass loss obtained here falls within the upper range of PET degradation reported in the literature and suggests an accelerated depolymerization process, likely involving combined oxidative and biological mechanisms.

Polypropylene (PP) generally exhibits greater resistance to degradation than PET due to its hydrophobic nature and lack of hydrolysable functional groups. Nevertheless, the 20% weight loss observed in this study exceeds many values reported for environmental exposure. Arutchelvi et al. [106] recorded only 5–15% mass loss for PP after 30–60 days under microbial composting conditions, while Napper and Thompson [103] reported 10–18% loss for PP films subjected to UV weathering in seawater. However, under more aggressive oxidative or thermophilic biodegradation conditions, comparable losses have been reported. Koutnik et al. [107] observed 15–22% weight loss of PP during 30 days of thermophilic composting, and Albertsson et al. [108] reported up to 18–25% mass reduction under controlled photo-oxidative aging. The 20% PP loss recorded in the present study therefore lies within the upper range of previously reported values and indicates enhanced oxidative chain scission, consistent with the FTIR-detected formation of carbonyl and hydroxyl groups.

Overall, the comparatively high mass losses of PET (28%) and PP (20%) over a short exposure period suggest that the experimental treatments significantly accelerated polymer degradation relative to natural weathering conditions. When considered alongside FTIR evidence of chemical structural modification, these results confirm progressive depolymerization and surface oxidation of both polymers, with PET showing greater susceptibility than PP. The findings are comparable to those reported under enzymatic, composting, or strongly oxidative environments and highlight the efficiency of the applied treatments in promoting plastic and microplastic degradation.

3.11. FTIR analysis of biodegraded PET microplastics by Treatments A and B

Fourier Transform Infrared Spectroscopy (FTIR) is a widely used technique for analysing the chemical structure of materials by identifying functional groups and chemical bonds [109]. Alongside scanning electron microscopy, FTIR is commonly employed to assess PET degradation [90]. In this study, FTIR was used to compare the chemical structure of untreated plastics and plastics degraded by Treatment A to detect changes induced by microbial activity. The control PET spectrum (Fig. 10.) showed characteristic absorption bands, including broad O-H stretching (3518–3261 cm^{-1}), strong C═O stretching at 1712.8 cm^{-1} (indicative of ester linkages), C-H stretching around 2952 and 2918 cm^{-1}, and distinct aromatic and ester-related peaks in the fingerprint region while the spectrum of PET treated with Treatment A exhibited significant changes such as a broader O-H band at 3338.3 cm^{-1}, new carbonyl peaks at 1640.0 and 1543.1 cm^{-1}, and shifts in the C-O and aromatic regions, suggesting hydrolysis of ester bonds and the formation of hydroxyl, carboxyl, and carboxylate groups. These modifications point to enzymatic activity by *Proteus sp.*, *Bacillus subtilis*, and *Pseudomonas sp.*, which collectively facilitated partial degradation of PET. The results are consistent with previous findings [110,111] showing that microbial degradation of PET leads to the formation of new functional groups and structural alterations due to hydrolytic cleavage.

The FTIR spectrum of the control PP and consortia a biodegraded PP plastic (Fig. 11) also displayed characteristic absorption bands consistent with the chemical structure of polypropylene. The FTIR spectrum of polypropylene showed characteristic peaks corresponding to C-H stretching vibrations (2996.8 cm^{-1}, 2957.2 cm^{-1}, and 2868.7 cm^{-1}), C-H bending vibrations (1457.4 cm^{-1} and 1377.5 cm^{-1}), C-C stretching and C-H rocking vibrations (1166.7 cm^{-1}, 1103.3 cm^{-1}, and 997.6 cm^{-1}), and tacticity-related C-H rocking vibrations (841.4 cm^{-1}), confirming its hydrocarbon backbone structure.

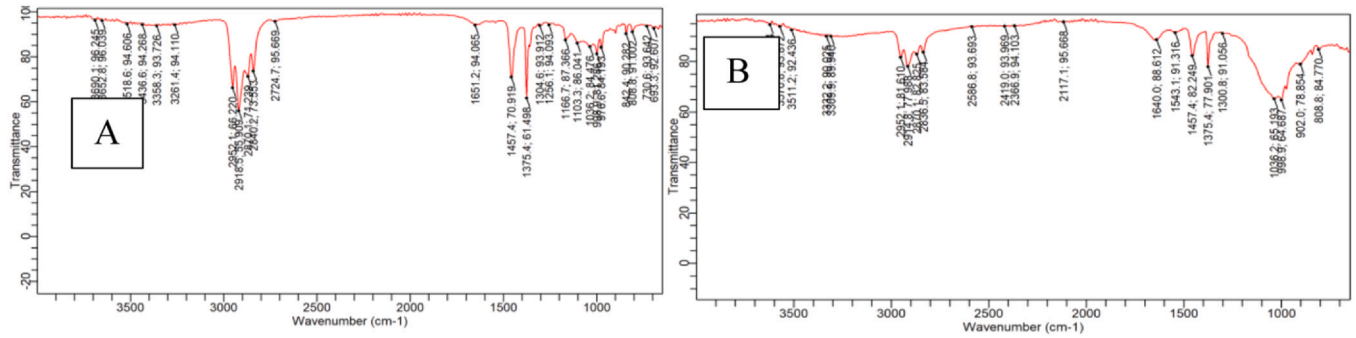

Fig. 10. Fourier transform infrared spectra of (A) un-degraded PET plastics and (B) consortia a biodegraded PET plastic.

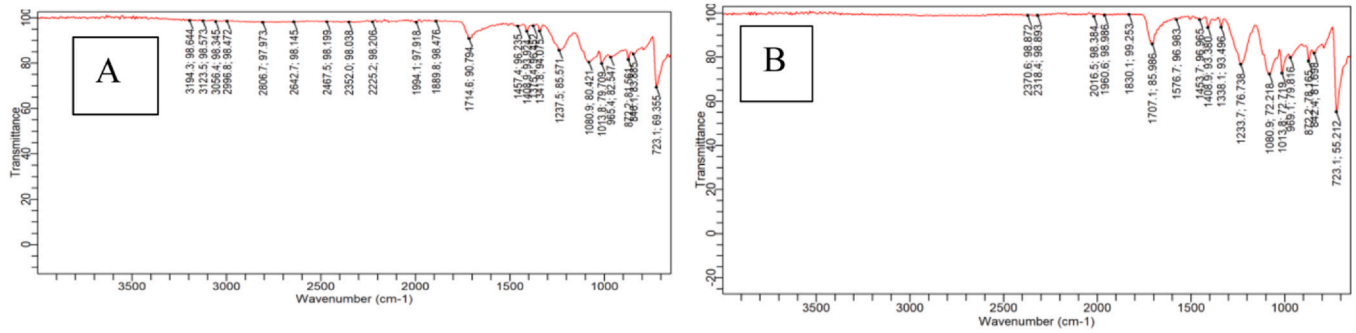

Fig. 11. Fourier transform infrared spectra of (A) un-degraded PP plastics (Control) (B) consortia a biodegraded PP plastic.

The FTIR spectrum of the biodegraded PP showed significant differences compared to the control, suggesting chemical modifications due to microbial degradation. The spectrum show signs of polypropylene degradation, including increased O-H content (3400–3300 cm^{-1}), formation of carbonyl groups (1707.1 cm^{-1}), modifications in hydrocarbon chains (2960–2870 cm^{-1}), emergence of new peaks indicating C=C double bonds (1640–1630 cm^{-1}) and C-O stretching (1233.7 cm^{-1} and 1080.9 cm^{-1}), and changes in bending regions and backbone structure, collectively suggesting oxidative degradation and modification of the polymer structure [112].

The differences between the FTIR spectra of control and biodegraded PP indicate that microbial action led to chemical modifications in the polymer structure. The increase in hydroxyl (-OH) and carbonyl (C=O) groups, as well as the formation of new C-O bonds, are clear indicators of oxidative degradation [113]. The observed oxidative degradation can be attributed to the synergistic metabolic activities of the consortia A that produce extracellular enzymes capable of breaking down the polymer chains. These enzymes, such as oxidases and peroxidases, initiate oxidation of the polymer surface, leading to the formation of reactive oxygen species (ROS) that further enhance the oxidative breakdown of the polymer chains [114]. The initial oxidation results in the formation of hydroxyl (-OH) and carbonyl (C=O) groups, while prolonged exposure to microbial enzymes can lead to chain scission and the formation of low-molecular-weight compounds such as alcohols, carboxylic acids, and esters [93]. Such microbial oxidation is a common mechanism in the biodegradation of polymers, where the microorganisms utilize the degradation products as a carbon source for growth and energy.

3.12. Scanning Electron Microscopy (SEM) of biodegraded PP and PET microplastics by treatments A and B

Scanning electron microscopy (SEM) was used to examine the surface morphology of microplastic particles before and after biodegradation treatment. It offers high-resolution visualization of surface modifications in polymers subjected to microbial treatment. The control sample of PET plastics (Plate IA) exhibited a smooth, uniform, and homogeneous surface, devoid of visible cracks, pits, or erosion marks indicating that the polymer structure remained intact and unaltered, confirming the absence of biodegradation activity while the SEM micrographs of the treated PET samples (Plates IC and ID) showed significant surface alterations characteristic of biodegradation. These included increased surface roughness, the presence of pits and cavities, as well as areas of deep erosion with brittle and porous textures. Such morphological changes are consistent with early-stage polymer degradation, likely caused by microbial colonization (Plate IB) or enzymatic hydrolysis, and suggest active breakdown of the PET matrix. The presence of eroded zones, brittle textures, and porous areas is indicative of polymer chain scission and surface disintegration, likely initiated by microbial enzymatic activity or acid hydrolysis. These microstructural changes provide strong evidence of microbial colonization and metabolic action, leading to the breakdown of the PET surface.

The visible degradation features confirm that Treatment A possess the capability to attach (Plate IB) and break down PET polymers. This supports the feasibility of using microbial treatment as a biotechnological approach for controlling microplastic pollution. Surface degradation is often the first step toward complete polymer mineralization, and such physical changes are prerequisites for further biochemical transformations [115].

These results are in agreement with previous studies that reported similar morphological alterations following microbial degradation of synthetic plastics. SEM features such as cracks, pits, and surface roughening in polyethylene films degraded by bacterial isolates. Similarly, Yang et al. [116] demonstrated the biodegradation of polystyrene and PET by *Ideonella sakaiensis* and other plastic-degrading microbes, where SEM images revealed erosion and fragmentation of polymer surfaces. The intact morphology of control plastic particles and the development of structural defects post-biodegradation, emphasizing the role of microbial enzymes in polymer surface breakdown.

The surface morphology of plastics degraded by microorganisms' transitions through distinct stages observable as shown in Plate I via microscopic techniques (SEM). Initially, plastic surfaces are smooth,

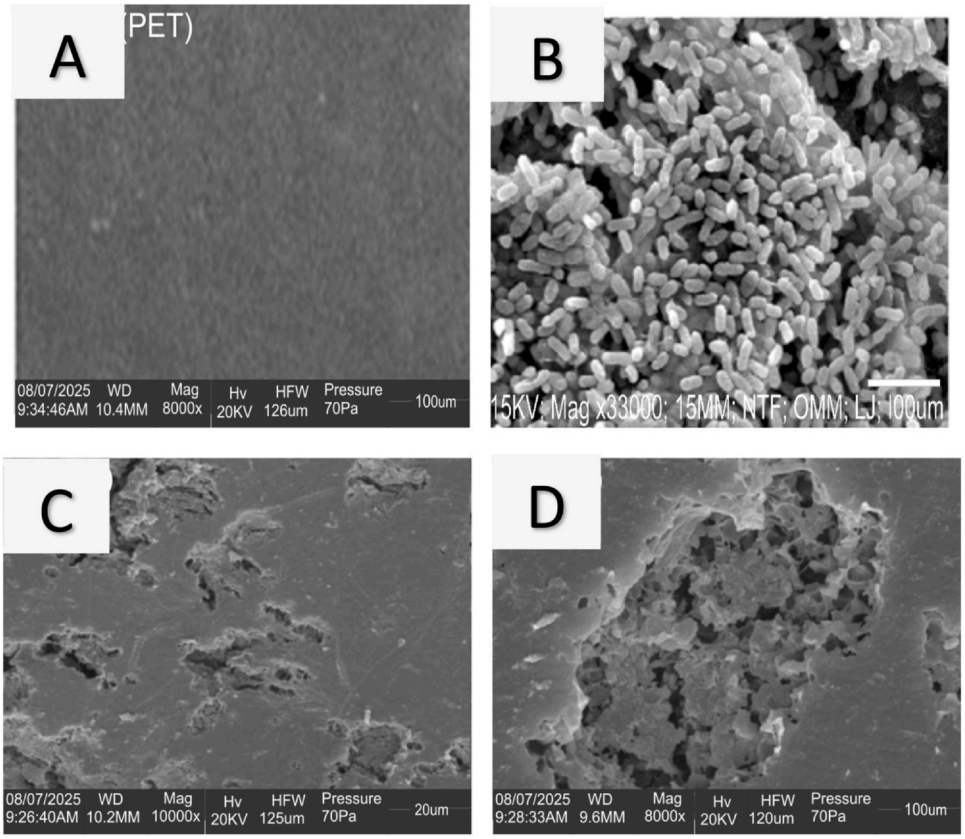

Plate I. SEM images of PET microplastics (A) control MP with colonized bacteria (B) and biodegraded (C and D) PET microplastics.

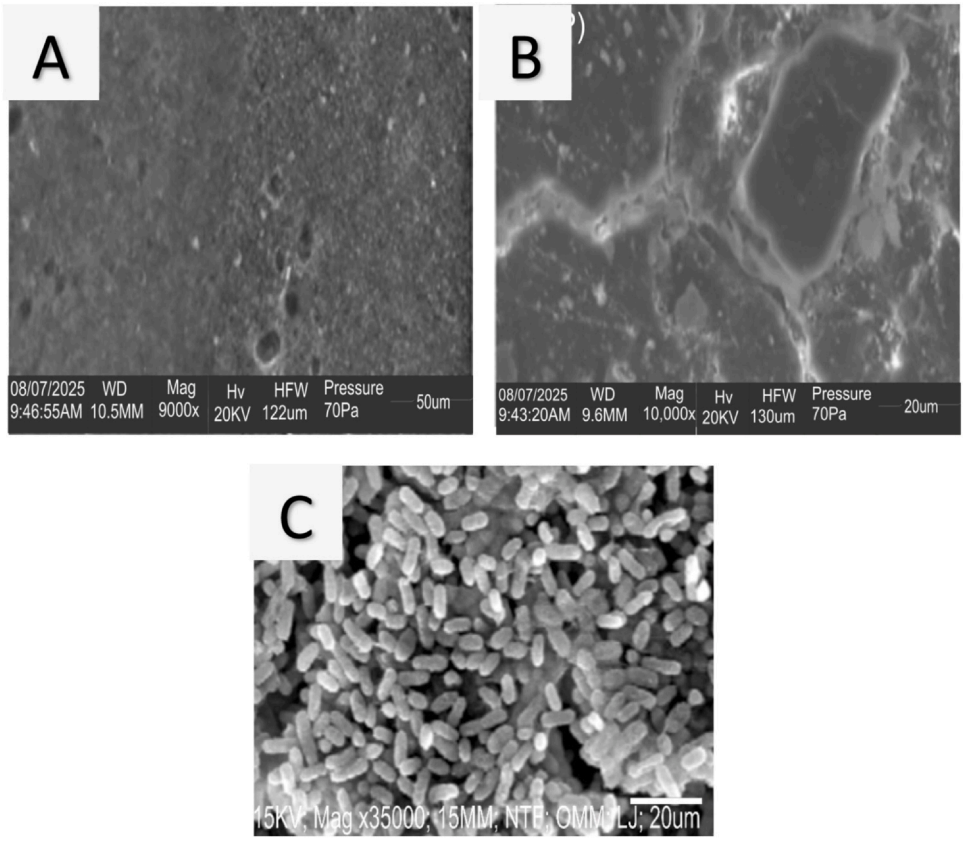

Plate II. SEM images of biodegraded PP microplastics by Treatments A (Plate II A) and Treatment B (Plate II B), and bacterial colonization (Plate II C).

hydrophobic, and structurally intact. Upon microbial colonisation, biofilms form, marking the onset of degradation. Microorganisms secrete extracellular enzymes such as hydrolases, esterases, and oxidases which disrupt polymer chains, leading to visible surface cracking, pitting, and increased roughness. Prolonged enzymatic activity results in fragmentation and erosion, with SEM revealing cavities and flake detachment. Ultimately, the plastic becomes porous and brittle, with collapsed structures indicating severe degradation and compromised mechanical integrity. These morphological changes confirm progressive microbial deterioration of plastic polymers [93].

The scanning electron micrographs of polypropylene (PP) microplastic particles following biodegradation treatment are presented in Plate II (A and B). The treated PP surfaces exhibited distinct morphological changes, including increased roughness, visible cavities, pits, and pronounced erosion of the polymer matrix. These features are characteristic of early-stage polymer degradation, likely resulting from microbial colonization, enzymatic hydrolysis, and associated metabolic activity.

These surface features are classic indicators of early-phase microbial degradation, typically resulting from prolonged microbial colonization and enzymatic attack on the polymer structure. The altered morphology of the PP microplastics strongly suggests that the microbial consortia adhered to the PP surface (Plate IIC) and initiated polymer breakdown through the secretion of extracellular hydrolytic enzymes. The physical damage observed supports the hypothesis that microbial strains involved possibly comprising proteolytic, oxidase- or esterase-producing bacteria produced metabolites capable of cleaving the hydrocarbon chains in PP [93]. The manifestation of fragmentation zones, ruptured textures, and crater-like formations is indicative of microbial metabolic activity leading to polymer chain scission, likely via oxidative or enzymatic mechanisms. These visible alterations mark the onset of surface erosion, which precedes further degradation stages such as molecular depolymerization and mineralization.

Similar surface-level morphological disruptions in synthetic polymers such as polyethylene and polystyrene following microbial degradation. The significance of the present study lies in its demonstration of structural degradation in polypropylene (PP), a polymer widely recognized for its high hydrophobicity, chemical stability, and resistance to microbial attack.

4. Conclusion

In this study, the total bacterial count varied with sampling location. Withj Elegushi Beach recording the highest total bacterial count, with an average of 10.6 × 104 CFU/g. The study recorded a total average bacterial count of 5.65×10^4 CFU/g and a mean concentration of 461 items/kg. *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Micrococcus luteus*, *Serratia marcescens*, *Alcaligenes faecalis*, *Bacillus mycoides*, *Bacillus polymyxa*, *Bacillus cereus*, *Bacillus subtilis*, *Staphylococcus epidermidis*, and *Proteus vulgaris*.

The present study demonstrated significant degradation of both polyethylene terephthalate (PET) and polypropylene (PP) within a 30-day exposure period, as evidenced by substantial mass loss and corroborated by FTIR spectral modifications. PET exhibited a higher percentage weight loss (28.0%) under Treatment A, while PP recorded a lower but still considerable loss (20.0%) under Treatment B. The greater susceptibility of PET is attributable to the presence of hydrolysable ester linkages in its backbone, which are prone to enzymatic and hydrolytic cleavage, whereas the more hydrophobic and chemically inert structure of PP confers comparatively higher resistance to degradation. The magnitude of weight loss observed for both polymers falls within, and in some cases exceeds, the upper range of values reported in previous laboratory and environmental studies, indicating that the applied treatments created conditions highly conducive to oxidative and/or biological depolymerization. The FTIR results, showing the emergence and intensification of oxygen-containing functional groups, further confirm progressive chain scission and surface oxidation as key degradation mechanisms. Collectively, these findings highlight the effectiveness of the experimental treatments in accelerating the breakdown of recalcitrant plastic polymers and underscore their potential relevance for mitigating microplastic persistence in the environment. Future studies should extend the exposure period beyond 30 days to evaluate long-term degradation kinetics and to determine whether the observed mass loss follows linear, exponential, or plateau trends over time. Quantitative analysis of molecular weight distribution using techniques such as gel permeation chromatography (GPC) would provide deeper insight into the extent of polymer chain scission and depolymerization. In addition, coupling FTIR with complementary spectroscopic and thermal analyses (e.g., Raman spectroscopy, DSC, and TGA) would allow more comprehensive characterization of structural and thermal changes during degradation.

Further research should also investigate the role of specific microbial consortia and enzymes in enhancing PET and PP degradation, including isolation and identification of dominant degraders and assessment of their metabolic pathways. Comparative studies under different environmental matrices (marine, freshwater, soil, and compost) and varying physicochemical conditions (temperature, pH, UV intensity, and oxygen availability) are recommended to better simulate natural settings and to elucidate the factors governing polymer weathering rates. Finally, evaluating the formation and fate of intermediate micro- and nanoplastic fragments, as well as potential ecotoxicological effects of degradation by-products, would be essential for a holistic understanding of the environmental implications of accelerated plastic degradation processes.

Authors agreement

All authors of this paper have read and approved the manuscript and its submission.

CRediT authorship contribution statement

H. S. Auta: Conceptualization, Supervision, Methodology.: **M. A. Murtadha, G. Aruwa:** Data curation, Writing- Original draft preparation: **Awono, A. T. Edzili, D. O. Aboyeji:** Visualization, Investigation, Formal analysis.: **M. M. Wuna**: Software, Validation.: **E. O. Balogun:** Writing- Reviewing and Editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ARUWA GABRIEL reports administrative support was provided by Federal University of Technology Minna Nigeria. ARUWA GABRIEL reports a relationship with Federal University of Technology Minna that includes: employment. If there are other authors, they 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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