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Degradation potential in aquatic environments of biofilms derived from banana peels (*Musa paradisiaca*)

Mabel L. Laz-Mero[1,2*], Miguel A. Tuárez-Párraga[2], Liceth J. Solorzano[3], Rosa A. Córdova-Mosquera[1], Ramona A. Panchana[4], Xavier A. Cedeño[2], Mario J. Bonilla[3], Mario D. Ninago[2,5]

[1] Department of Chemical Processes, Food, and Biotechnology, Faculty of Engineering and Applied Sciences, Technical University of Manabí, Portoviejo 130104, Ecuador
[2] Faculty of Applied Sciences to Industry, National University of Cuyo, San Rafael, M5600APG, Argentina
[3] Department of Agroindustrial Processes, Faculty of Agricultural Sciences, Technical University of Manabí, Portoviejo 130104, Ecuador
[4] Department of Civil Construction, Architecture, and Geology, Faculty of Engineering and Applied Sciences, Technical University of Manabí, Portoviejo 130104, Ecuador
[5] Institute of Engineering and Applied Sciences to Industry (ICAI-CONICET), San Rafael, M5600APG, Argentina

ABSTRACT

Plastic pollution in aquatic environments poses a serious environmental challenge, demanding the implementation of sustainable and effective solutions. The aim of this study is to compare the biodegradation of biofilms in freshwater and saltwater. The biofilms were made from banana peel starch, using three formulations (F1, F2, and F3), which were subjected to degradation tests in controlled environments, simulating variations in temperature, pH, and the presence of microorganisms. Biofilms were prepared by drying a starch suspension, and then exposed to aquatic conditions for 5 days. Degradation was assessed through weight measurements, visual observations, and water solubility analysis. The results demonstrated significant degradation on the first day, suggesting that these biofilms could serve as a more sustainable alternative to conventional plastics in aquatic environments. The findings of this research highlight the potential of banana peel-based biofilms to mitigate plastic waste. Future studies should focus on optimizing their formulation and evaluating their feasibility for large-scale industrial production.

Keywords: bioplastics, banana peels, biodegradability, aquatic environments, plastic pollution.

INTRODUCTION

Bioplastics have emerged as a promising alternative to conventional plastics derived from non-renewable resources, offering a viable solution to reduce environmental pollution and mitigate the impacts of climate change. Among the various biodegradable materials used in bioplastic production, banana peels (*Musa paradisiaca*) have garnered significant attention due to their abundance, low cost, and excellent biocompatibility. Despite their potential, the biodegradability of these bioplastics in aquatic environments remains a critical area of investigation that requires comprehensive assessment. Moreover, plastic waste poses a severe economic and environmental threat, affecting key sectors such as tourism, fisheries, and maritime transport. Alarmingly, up to 4% of global annual plastic production ends up in the oceans, where it accounts for more than 80% of marine debris (Folino et al., 2023).

To partially address the challenges associated with the production and end-of-life of plastic products, bioplastics have been developed over the past decades as a viable alternative to conventional plastics. This diverse family of materials encompasses a wide range of compositions and properties. In fact, bioplastics differ significantly from one another, primarily due to the type of polymer they are made from and their structural

characteristics, which largely determine their environmental persistence once released. The term "bioplastics" encompasses both biobased plastics derived from renewable sources like plant materials or organic waste, and biodegradable plastics, which can break down naturally under specific conditions. With respect to the question, it should be noted that not all bioplastics are biodegradable; some plastics of petrochemical origin can also be labeled as bioplastics due to their biodegradable properties. Therefore, a bioplastic is a material that is either bio-based (Folino et al., 2023; Karan et al., 2019).

Bioplastics were initially introduced as ecofriendly alternatives with properties comparable to those of traditional plastics. A bioplastic is considered biodegradable if it can break down into carbon dioxide under aerobic conditions or into methane, carbon dioxide, inorganic compounds, and new cellular biomass under anaerobic conditions, through the action of natural microorganisms (Lavagnolo et al., 2024).

Between 2010 and 2025, an estimated 100 million tons of plastic waste are expected to enter the oceans. This has raised increasing concern about the impact of plastics on marine ecosystems. Once in the ocean, plastics cause a wide range of environmental and economic consequences (Dilkes-Hoffman et al., 2019).

The oceans are a primary destination for plastic waste, with an estimated 10 to 20 million tons entering them annually (Borrelle et al., 2020; Jambeck et al., 2015; Thompson et al., 2004). While less research has been conducted on freshwater ecosystems, evidence indicates that plastic pollution in these environments is comparable to that found in marine ecosystems (Peng et al., 2017). Terrestrial ecosystems are also impacted by plastic pollution, with agricultural practices and wastewater treatment being primary sources (Won et al., 2020; Ventura et al., 2024).

Biodegradable polymers were developed to mitigate plastic-related pollution. Their biodegradation occurs in three stages. The first stage, known as biodeterioration, involves the alteration of the polymer's mechanical, chemical, and physical properties due to the growth of microorganisms on its surface. The second stage, bio-fragmentation, involves the breakdown of polymers into oligomers and monomers through the action of microorganisms. Finally, in the assimilation stage, atoms from these polymeric fragments are integrated into microbial cells, providing the carbon, energy, and nutrients needed to convert the plastic's carbon into CO_2, water, and biomass (Riera and Palma, 2018).

The growing concern over plastic pollution in aquatic ecosystems has led to an urgent drive for the development of sustainable and biodegradable alternatives. Conventional plastics, derived from non-renewable resources, represent a significant threat to marine biodiversity and the integrity of aquatic ecosystems.

In response to the escalating environmental challenge of plastic pollution, scientific research has increasingly focused on developing bioplastics, an innovative and sustainable class of materials. Among the renewable resources being investigated for bioplastic production, banana peels (Musa paradisiaca) have emerged as a particularly promising option. Abundant, cost-effective, and rich in natural polymers such as cellulose and lignin, banana peels present a compelling alternative for bioplastic production. These peels offer significant potential, as they can produce bioplastics with desirable mechanical and thermal properties, making them a viable and environmentally responsible solution to reduce dependence on conventional plastics.

This study aims to evaluate the biodegradability of bioplastics made from banana peels in aquatic environments. Through a thorough and detailed investigation, we seek to understand the physicochemical characteristics of these bioplastics in both freshwater and marine conditions, while also examining the interactions between the relevant variables. This approach not only provides a comprehensive understanding of the biodegradability of banana peel bioplastics but also their potential to reduce plastic pollution in aquatic ecosystems.

MATERIALS AND METHODS

This study employed an experimental approach to obtain and characterize biofilms derived from starch extracted from plantain (Musa paradisiaca) peels. To ensure consistency in the starch's final properties, green plantain peels were meticulously collected from local plantations, selecting them based on uniformity in size and maturity stage (Gómez Sierra and Jiménez-Sánchez, 2022).

The peels were then washed with deionized water to eliminate any surface impurities and

contaminants, followed by air-drying at room temperature to prevent the degradation of cellulosic polymers (Lora et al., 2022). Starch extraction from the plantain peels was carried out using a wet method adapted from Aristizábal and Sánchez (2007) y Olawoye et al. (2022), involving a series of sequential steps.

First, the previously pulverized peels were soaked in water at a ratio of 1 liter per 2 kg of raw material to enhance starch release during the wet milling process. The resulting mixture was then filtered through fine mesh screens to separate the starch from fibers and other impurities, yielding a suspension that was left to settle for 24 hours to allow sediment formation. Afterward, the excess water was carefully decanted, and the wet starch was weighed (Hernández-Carmona et al., 2017).

The purified starch underwent successive washing steps to achieve a high degree of purity, a crucial parameter for ensuring the quality and performance of the resulting biofilms. Subsequently, the starch was dried in a Universal Memmert Single DISPLAY oven at 60 °C for 24 hours. After drying, it was finely sieved using a #200-0.074 mm to obtain a uniform particle size distribution and was then stored in Kraft paper sleeves under controlled conditions until its use in biofilm formulation.

Physicochemical analyses were conducted to assess the quality and characteristics of the extracted starch. Moisture content was measured using the oven-drying method, following the procedure described by Arévalo Hernández (2020) and standardized by the AOAC 930.15 (AOAC International, 1999). To this end, a 1-gram sample was dried in a Universal Memmert Single DISPLAY oven at 80 °C for 3 hours.

After cooling in a desiccator for 30 minutes, the final weight was recorded to determine the moisture content, calculated as the difference between the initial and final weights. The ash content, indicative of the inorganic mineral composition, was quantified following the AOAC 942.05 standard method (AOAC International, 2012). One gram of the sample was calcined at 600 °C in a Thermolyne flask for 45 minutes. The resulting residue was then cooled in a desiccator and weighed to determine the ash content. The amylose-to-amylopectin ratio in starch was analyzed using spectrophotometric techniques. Prepared solutions were measured for absorbance at 620 nm using an Evolution 60S spectrophotometer. Amylose concentration was quantified using a standard curve, while amylopectin content was calculated by difference (Muñiz Acuña et al., 2023).

The bioplastic was synthesized using high-quality reagents sourced from reputable suppliers: glycerin and acetic acid from Maquimsa, polyvinyl alcohol (PVA) from Labsupply, and starch extracted from banana (Musa paradisiaca) peels. The polymeric matrix was formed by combining starch with glycerin, acetic acid, and PVA under controlled temperature and agitation conditions, ensuring uniformity in the final product (Vicente Flores, 2018).

The procedure, following the methodology outlined by Pizá et al. (2017), began with the precise weighing of reagents, which were then mixed in a beaker. The mixture was subsequently heated to a temperature of 70–73 °C to achieve gelatinization. Table 1 presents the formulations used in the bioplastic manufacturing process, ensuring accurate replication and evaluation of these sustainable materials.

The homogeneous mixtures were allowed to cool before being poured into molds and dried in a Universal Memmert Single Display oven at 50 °C for 16 hours. The biofilm thickness was then measured at multiple random points on each sample using a HEEPDD digital micrometer (Yoplac-Tafur et al., 2020).

To analyze biodegradation, we started by thoroughly characterizing the river and ocean environments. We collected water samples directly from Crucita Beach (-0.873310, -80.541688) and the Portoviejo River (-1.033890, -80.490847).

For river and seawater, the parameters evaluated included conductivity, pH, temperature, total dissolved solids (TDS), chloride, alkalinity,

Table 1. Bioplastic formulations (% by weight)

N°	Ingredients	F1	F2	F3
1	Water	88.56%	86.06%	83.56%
2	PVA	2.50%	5.00%	7.50%
3	Starch	5.00%	5.00%	5.00%
4	Glycerin	2.23%	2.23%	2.23%
5	Vinegar	1.71%	1.71%	1.71%

chemical oxygen demand (COD), nitrogen, and 5-day biochemical oxygen demand (BOD), in accordance with the relevant standards.

The physicochemical parameters of river and seawater were assessed, including conductivity (ISO 22719:2008), pH (ISO 10523:2008), temperature, TDS (ISO 7888:1985), chloride (ISO 9297:1989), alkalinity (ISO 9963-1:1994), COD (ISO 15705:2002), nitrogen (ISO 5663:1984), and 5-day BOD (ISO 5815-1:2019), in accordance with the corresponding international standards.

Finally, degradation tests were conducted in aquatic environments (sea and river) to assess the mass loss of the biofilms, following the experimental protocol based on ASTM D7473/D7473M-21. Bioplastic sheets (5 × 5 cm) were immersed in seawater under controlled conditions to simulate a closed marine environment. Samples were placed in sterilized glass containers and maintained at room temperature (approximately 25 °C), with precautions taken to avoid exposure to ultraviolet light, thereby preventing photodegradation.

The test lasted for five days, during which the initial weight of the sheets was recorded. At the end of the testing period, the samples were removed, dried at 80 °C for one hour, and then weighed again. The difference between the initial and final weights was used to calculate the percentage mass loss, providing a quantitative measure of degradation under marine conditions.

Additionally, the BOD/COD ratio was determined to calculate the biodegradability index of the bioplastics, enabling the evaluation of their environmental impact under natural conditions. All experiments were conducted in triplicate to ensure the reproducibility of the results. The data obtained were subjected to statistical analysis using ANOVA, with a significance level set at $p < 0.05$ to assess the differences between formulations.

RESULTS AND DISCUSSION

Extraction and physicochemical characterization of starch from banana peel

This study reported a starch yield of 9.8% from plantain peels, which falls within the range reported by other authors. For example, Francis et al. (2023) obtained a yield of 7.5% using an alkaline extraction method, while Putra et al. (2022) achieved a yield of 10.2% with a combination of enzymatic and mechanical methods**.** These values are comparable to the yield obtained in this study, suggesting that the methodology employed is efficient. However, Rivadeneira et al. (2023), who used different processing conditions for plantain peels, reported higher yields, reaching up to 12.4%. These yield variations may be attributed to differences in extraction techniques and the characteristics of the plant material, underscoring the importance of optimizing process parameters to enhance both the quantity and quality of the recovered starch.

Moisture content

The results of this trial indicate a moisture content of 12.5%, in contrast to recent studies such as those by Marta et al. (2022) and Olagundoye and Morayo (2022), which reported lower values of 10.37% and 10.15%, respectively. This suggests that the material studied in this research may exhibit higher water retention or reduced desiccation, potentially influenced by processing or storage conditions. The maximum allowable value according to CODEX STAN 152-1985 is 15.5%, meaning that the obtained value falls within the permissible range, thereby ensuring the material's quality in terms of stability and preservation.

Ash content

The ash analysis yielded 0.39%, a value significantly higher than the 0.12% reported by Miah et al. (2023), but lower than the range of 11.91% to 14.17% reported by Estribillo et al. (2022). However, the latter results appear to be relatively high compared to the present study, which may be attributed to variations in the mineral composition of the material or the analytical methods employed. According to NTE INEN 1456 (1986-08), the maximum allowable limit is 0.40%, meaning the obtained value falls within the established parameters, ensuring the material's adequate purity in terms of inorganic content.

Amylose and amylopectin content

Regarding the content of amylose and amylopectin, the results indicate 0.8% amylose and 99.2% amylopectin, values that generally align with those reported by Miao et al. (2017), who found 3.35% amylose and 96.65% amylopectin. However, discrepancies are observed when compared to the data of Li et al. (2022), who recorded 17.19% amylose and 82.81% amylopectin,

reflecting a higher proportion of amylose. This variability may be attributed to differences in starch sources or specific processing conditions. ISO 6647-1:2020 outlines standard methods for determining these fractions, ensuring that the results are consistent with international standards.

Characterization of bioplastics films

The experimental thickness of the obtained biofilms was 0.17 ± 0.02 mm, which is significantly lower than the values reported in the literature. For instance, Nasir and Othman (2021) and Shineh et al. (2023) obtained biofilms with a thickness of approximately 3 mm using cassava starch and glycerol as a plasticizer. Similarly, Crouzet et al. (2014) reported thickness values ranging from 1.62 mm to 3.03 mm in banana starch-based films. These differences may be attributed to variations in formulation, processing conditions, or structural properties of the starch sources. These differences may be attributed to variations in formulation and processing parameters, such as plasticizer type, starch concentration, and drying conditions, all of which can significantly influence biofilm thickness. Optimizing these factors in future research could enhance film properties, tailoring them for specific applications

The experimental moisture content obtained was 16.69%, closely aligning with the value reported by Shanbhag et al. (2023) (16.39 ± 0.16%). However, it is significantly lower than the levels documented by Taweechat et al. (2021), who reported moisture contents ranging from 26.3% to 33.7% in starch-based biofilms. These differences may be attributed to variations in formulation, plasticizer content, or drying conditions. Variations in moisture percentages can be attributed to differences in drying methods and formulations, highlighting the importance of optimizing processing conditions to achieve moisture levels within the normative ranges established by ASTM D6980-17. Moreover, excessive moisture content in biofilms intended for food packaging may promote microbial growth on the surface of packaged products (Kaewprachu et al., 2017; Pattarasiriroj et al., 2020), compromising their safety and shelf life.

Finally, regarding the solubility of the biofilms, the experimental value was 62.48%, which is comparable to the results reported by Jiménez-Regalado et al. (2021), who found a solubility of 68.84% in starch-based biofilms. In contrast, Navarrete-Tumbaco et al. (2023) documented a significantly lower solubility of 39.39%. These differences may be attributed to variations in the type of starch used, the presence and concentration of plasticizers, and the amount of residual water in the films, all of which directly influence solubility. This underscores the importance of precisely controlling these parameters to develop biofilms with tailored properties for industrial applications

Evaluation of biofilm degradation

The results presented in Table 2 indicate that Water_type and Formulations exert a significant influence on the biodegradability of the biofilms ($p < 0.05$). However, no significant interaction between these variables was observed ($p > 0.05$).

Additionally, the results of this study reveal significant data on the biodegradation of bioplastics made from banana peels in aquatic environments. As shown in Figure 1, the bioplastics underwent considerable degradation in both river and sea water, with a mass reduction of up to 89% by the end of the evaluation. This suggests that these bioplastics have a high capacity to decompose in water, which aligns with the findings of Emadian et al. (2017) and Lavagnolo et al. (2024), who observed similar biodegradation rates in organic-based bioplastics.

The results of this analysis suggest that both the type of environment and the application of PVA independently influence the biodegradability of bioplastics. This aligns with previous studies by Folino et al. (2020) and Kumar et al. (2020), which validate the influence of the aquatic

Table 2. ANOVA results for the effects of Water_type and Formulations

Source of variation	Df	Sum Sq	Mean Sq	F value	p-value
Water_type	1	998	998	252.901	1.99e-09
Formulations	2	7136	3568	904.557	8.18e-14
Formulations : Water_type	2	24	12	3.056	0.0846
Residuals	12	47	4		

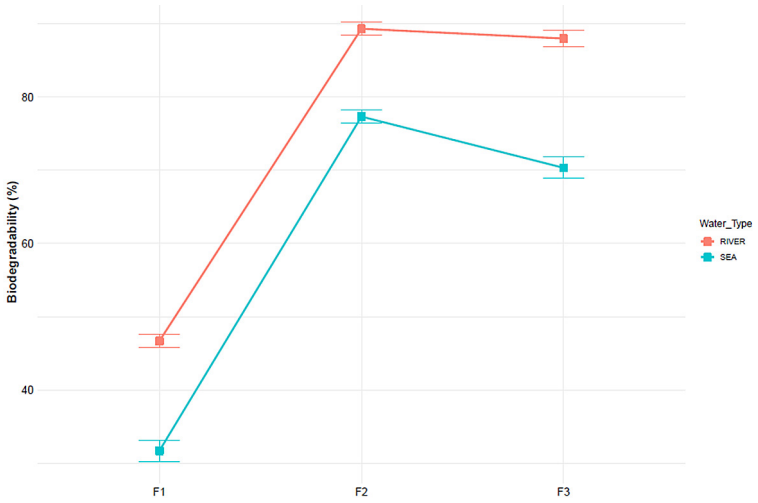

Figure 1. Degradation rate of bioplastics in river and sea water

environment on the biodegradation of polymeric materials. Variations in salinity, temperature, and the biological composition of marine and river ecosystems can significantly affect the microbial activity responsible for degradation, potentially explaining the differences observed in biodegradability between the two environments evaluated.

On the other hand, recent research has indicated that the biodegradability of bioplastics is also influenced by factors such as exposure to sunlight (or UV radiation) and the availability of nutrients in aquatic environments (Ali et al., 2023). These conditions can influence microbial activity, potentially accelerating the rate at which bioplastics degrade. Additionally, it is clear that an increase in the percentage of PVA significantly affects the biodegradability of the bioplastics, corroborating the findings of Lim et al. (2021). In their study on the properties and biodegradability of bioplastics based on corn starch and PVA, they demonstrated that the concentration of PVA influences both the structural characteristics and biodegradation properties of bioplastics, rendering them more susceptible to microbial degradation. Furthermore, Diyana et al. (2021) note that higher concentrations of PVA enhance the plasticity of the bioplastics, thereby facilitating microbial colonization and accelerating the degradation process.

It should be noted that the biofilms began to show signs of degradation from the first day of the study. This early degradation suggests that bioplastics can be rapidly colonized by microorganisms in the aquatic environment, facilitating their decomposition and thereby reducing their persistence in the ecosystem. Similar early degradation patterns have been reported in other studies, such as those by Brdlík et al. (2021) and Sathiaseelan et al. (2024), which highlight that the chemical characteristics of bioplastics play a critical role in their degradation, influencing both their interaction with microorganisms and their response to environmental conditions.

With the application of 2.5% PVA, both environments exhibit similar biodegradation behaviors. However, as the PVA concentration increases, significant differences emerge, particularly in river water environments, where biodegradability is notably higher. This indicates that the addition of PVA does not result in a uniform degradation effect across all aquatic environments. In the marine environment, the formulation with 5% PVA reaches its maximum biodegradability, but at 7.5% PVA, there is a slight reduction in degradation

This may suggest a saturation point or nonlinear behavior, where increasing the PVA concentration beyond a certain threshold does not result in a proportional increase in biodegradability. In contrast, in the river environment, biodegradability increases steadily up to 7.5% PVA, reaching the highest values observed among all combinations studied. Studies by Maity et al. (2021) and Shaji et al. (2024) have shown that the biodegradability of plastic materials in different aquatic environments does not follow a linear pattern. The application of PVA in biofilms appears to have a limited effect on degradation, pointing to the need for further research, particularly in marine environments (Alonso-López et al., 2021). As depicted in Figure 2, both aquatic environments and the different PVA

concentrations in the formulations significantly affect biodegradability levels. With increasing PVA percentages, biodegradability shows a clear enhancement, indicating that higher concentrations of PVA facilitate greater microbial degradation of the material (Elgharbawy et al., 2024).

These findings hold significant potential for biopackaging research, particularly in optimizing formulations and environmental conditions to enhance degradation rates. The results demonstrate that biofilms exhibit a substantially higher degradation rate compared to petroleum-based polymeric materials, as reported by Cheng et al. (2022) and Dhanraj et al. (2022).

Characterization of aquatic environments

Before and after conducting the biodegradation tests with the films, various physicochemical parameters were analyzed to assess the quality of the water used. These parameters, presented in the following figures, include conductivity, alkalinity, pH, chlorides, TDS, COD, nitrogen, and BOD. The results are presented comparatively, providing a clear overview of the variations in these parameters across the different environmental conditions. In Figure 3, the conductivity results for seawater show values of 47 µS/cm, while river water recorded a significantly lower value of 0.442 µS/cm. This marked difference in conductivity can be attributed to the higher concentration of dissolved ions in seawater, where the presence of cations such as sodium, potassium, calcium, and magnesium, as well as anions like carbonates, bicarbonates, and sulfates, enhance its ability to conduct electricity (Pawlowicz, 2008; Yang et al., 2021).

Although no significant variations were observed in the conductivity of seawater after the introduction of bioplastics, a notable increase of up to 0.467 µS/cm was recorded in river water following the incorporation of the biofilms. This suggests a potential interaction between the bioplastics and the ions present in the water. Such

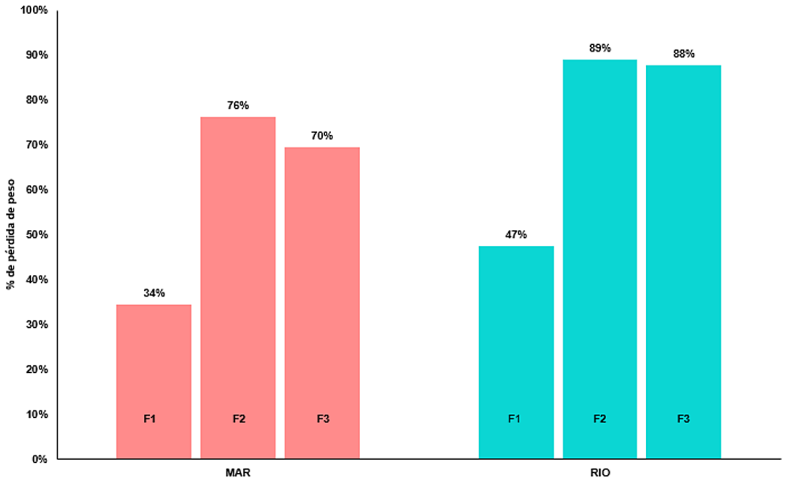

Figure 2. Effect of PVA percentage on the biodegradability of bioplastics in different aquatic environments

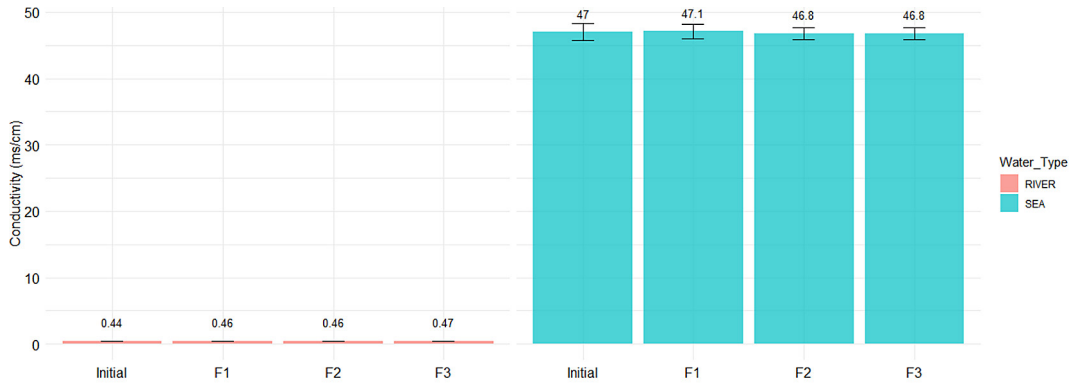

Figure 3. Variation in conductivity in seawater and river water

an increase could have important implications for water quality and the aquatic ecosystem, as changes in conductivity can influence biodiversity and ecological functions (Syeed et al., 2023).

Water alkalinity is primarily caused by the presence of salts derived from weak acids and strong bases, which act as buffers to mitigate the drop in pH that can result from the addition of acids (Ahmad et al., 2023). While a minimum alkalinity level of 20 mg $CaCO_3$/L is internationally recognized as essential to maintaining the health of aquatic ecosystems, no specific limit is established in Ecuadorian regulations (Sagñay Lema, 2023). In this study, the alkalinity values measured by titration were 60 mg $CaCO_3$/L for seawater and 108 mg $CaCO_3$/L for river water as shown in Figure 4. Following the addition of bioplastics, a reduction in alkalinity was observed in river water, with values decreasing from 78 to 72 mg $CaCO_3$/L. Conversely, in seawater, the alkalinity increased, with values ranging from 72 to 78 mg $CaCO_3$/L. These changes can be attributed to chemical interactions between the bioplastic components and specific ions present in the water, such as carbonates and bicarbonates. It has been shown that at high pH values, between 7.00 and 9.00, bicarbonates predominate and contribute to alkalinity (Kerr et al., 2021).

The initial characterization of seawater revealed a slightly alkaline pH of 7.16, while the river water showed an acidic pH of 6.44. The data, presented showed no significant changes in pH in any of the samples after the addition of the bioplastics. These results are notable as they indicate that the pH of seawater remains within the acceptable range for the preservation of aquatic life, which is established between 6.5 and 9.5 (Ministerial Agreement 097-A, 2015).

Chloride ion (Cl^-) forms highly soluble salts and is commonly associated with sodium ion (Na^+), especially in saline waters. Freshwaters typically contain between 10 and 250 ppm of chlorides, although much higher concentrations are not uncommon (Hong et al., 2023). In contrast, brackish waters can have chloride concentrations ranging from hundreds to thousands of ppm, while seawater contains approximately 20,000 ppm chloride (Qin et al., 2023; Zaman et al., 2018).

Figure 5 illustrates that seawater has a chloride concentration of 8663.2 mg/L, whereas river water contains 40 mg/L of chlorides. In the samples analyzed with bioplastics, a reduction in chloride concentrations was observed, with the lowest values recorded at 4331.6 mg/L for SEA - F2 and 25 mg/L for RIVER - F3. According to Ecuadorian regulations, there is no established limit for chloride concentration in seawater, whereas the limit for river water is set at 1000 mg/L (Ecuadorian Ministry of the Environment, 2002). In terms of temperature, seawater registered 21.6 °C, while river water measured 21.4 °C. The addition of bioplastics did not result in significant changes in the temperature of the samples. This temperature range remains well below the 35 °C threshold established by Ecuadorian regulations for the conservation of aquatic and wildlife in fresh, marine, and estuarine waters (Instituto del Agua, 2024).

Total dissolved solids (TDS), which primarily consist of inorganic salts such as calcium, magnesium, potassium, and sodium, along with bicarbonates, chlorides, and sulfates, may also include small amounts of dissolved organic matter in water (Adjovu and Ahmad, 2023; Boyd, 2020).

Figure 6 illustrates that seawater has a concentration of 24,000 ppm, which is substantial for this type of water; these concentrations are typically expressed in parts per thousand (ppt),

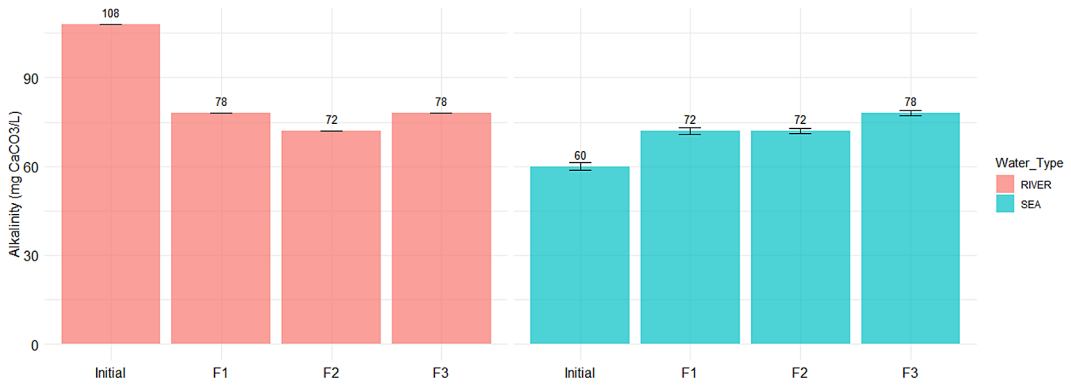

Figure 4. Variation in alkalinity in seawater and river water

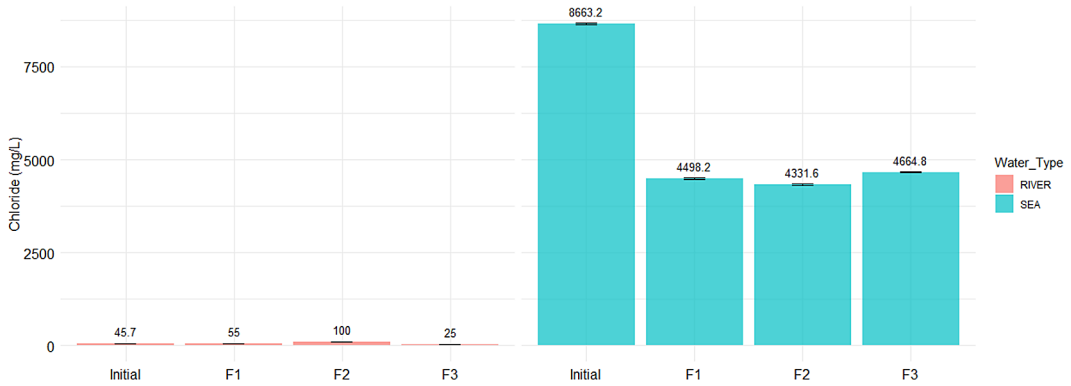

Figure 5. Chloride (Cl-) variation in seawater and river water

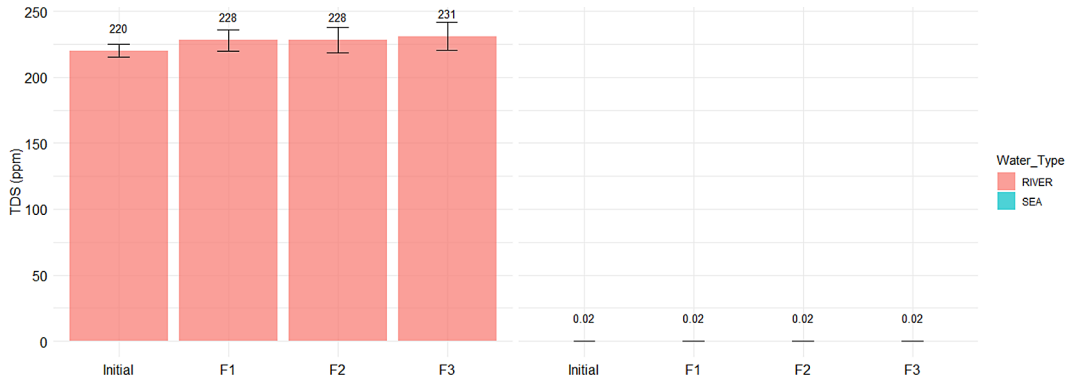

Figure 6. Total dissolved solids (TDS) variation in seawater and river water

equivalent to 24 ppt (Hach, n.d.). In contrast, river water presents a level of 220 ppm, consistent with typical dissolved solid concentrations in freshwater (Carbotecnia, 2021). The addition of bioplastics to both types of water did not result in significant variations in TDS levels, suggesting that the bioplastics do not affect water quality in terms of TDS. It should be noted that while Ecuador lacks a specific regulatory criterion for TDS, monitoring this parameter is crucial for evaluating water quality (Noori et al., 2023).

The total nitrogen analysis, conducted using Kjeldahl's methodology, revealed concentrations of 16.8084 mg/L in seawater and 81.2406 mg/L in river water. Notably, significant increases in nitrogen levels were observed in samples SEA-F3 and RIVER-F3, as shown in Figure 7. These values exceed the maximum limits set by Ecuadorian regulations, which establish a threshold of 40 mg/L for seawater and 50 mg/L for river water (Cámara de Industrias y Producción, 2013; Ministerio del Ambiente de Ecuador, 2002). Elevated nitrogen concentrations are concerning, as they can contribute to eutrophication, leading to degradation of water quality and adverse effects on aquatic ecosystems (Acuña and Salinas, 2020).

COD, which reflects the amount of oxygen required to oxidize organic matter to CO_2 and H_2O, is a key indicator of contamination in water bodies. In this study, COD levels of 2762 mg/L were observed in seawater and 1030 mg/L in river water, evidencing the presence of pollution in both types of water, as detailed in Figure 8. Furthermore, the incorporation of bioplastics increased the COD values in both aquatic matrices, probably due to the organic compounds present in the bioplastics (Phosri et al., 2022). In industrial waters, COD levels typically range from 50 mg/L to 2000 mg/L, with some industries reaching as high as 5000 mg/L, depending on the specific type of activity conducted (GC Tratamiento, 2021). The results obtained in this study exceed the limits established by Ecuadorian regulations for the preservation of aquatic life, which set a maximum of 400 mg/L for seawater and 100 mg/L for river water (Ministerio del Ambiente, 2015). These elevated COD levels may pose a threat to water quality and aquatic ecosystems.

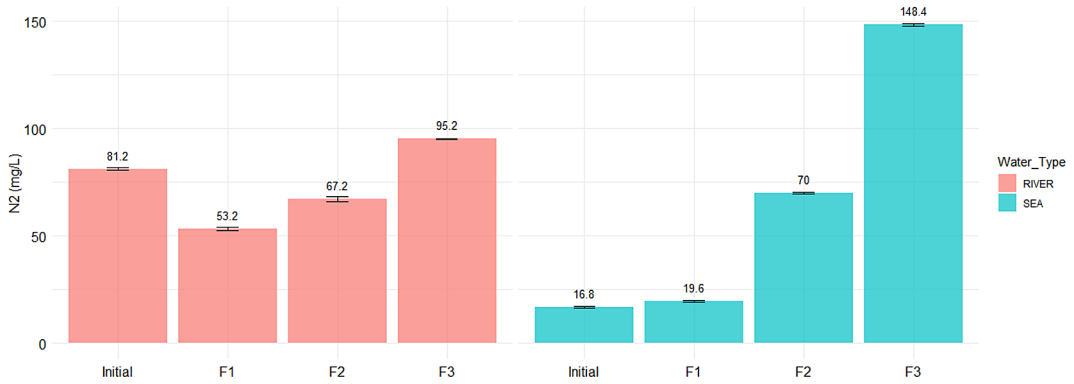

Figure 7. Variation of total nitrogen in seawater and river water

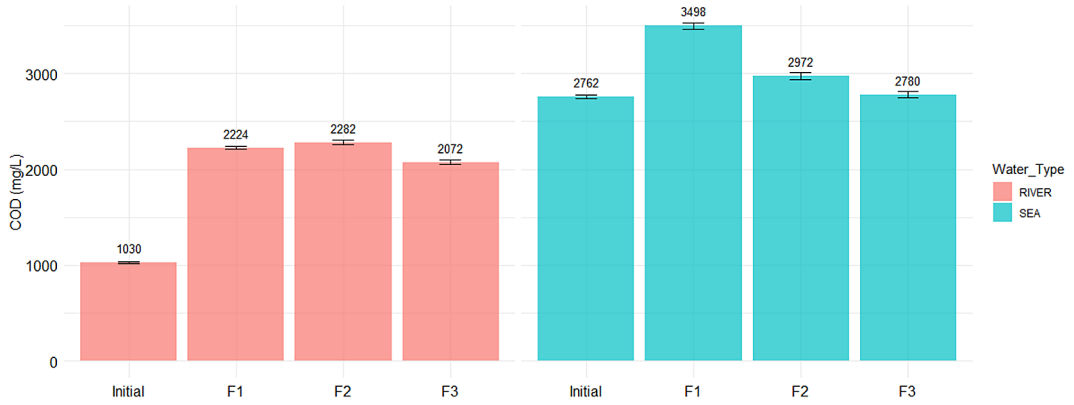

Figure 8. Variation of COD in seawater and river water

The study of BOD is fundamental for assessing the amount of oxygen consumed by microorganisms during the degradation of biodegradable compounds under aerobic conditions (Harrison et al., 2018). In this analysis, the incorporation of bioplastics led to an increase in BOD levels in both water bodies, with initial values of 10.1 mg/L in seawater and 21.3 mg/L in river water (Figure 9). These values exceed the limits set by Ecuadorian regulations for the preservation of flora and fauna, which establish a maximum of 200 mg/L for seawater and 100 mg/L for river water (Méndez-Ruiz et al., 2023). The observed increase in BOD suggests a higher organic matter, which could compromise water quality and the health of aquatic ecosystems by reducing available oxygen levels

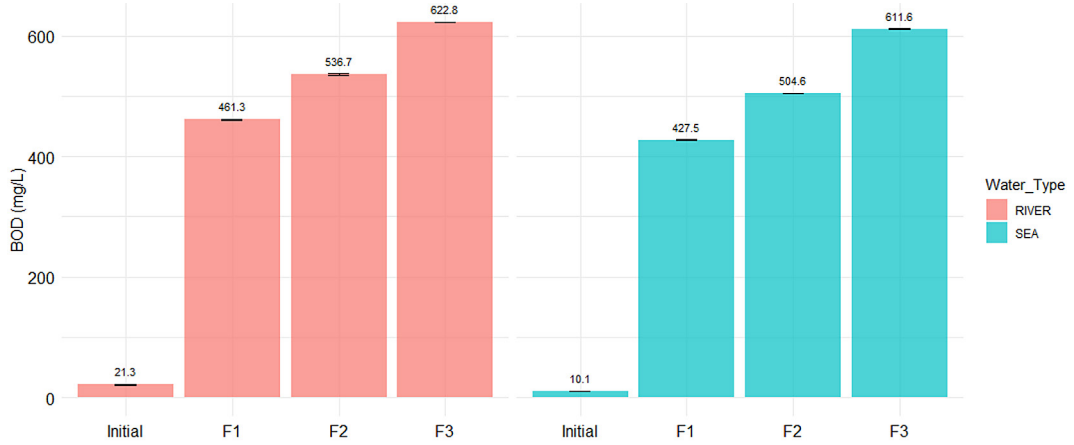

Figure 9. BOD variation in seawater and river water

for other aquatic organisms (Phosri et al., 2022). Additionally, the biodegradability index (IB) was calculated using the ratio of biochemical oxygen demand (BOD_5) to COD, with the formula: IB = (BOD_5/COD) × 100. The results obtained in the absence of bioplastics in seawater and river water were as follows: 0.0036 for seawater and 0.020 for river water, indicating a low rate of biodegradation. In contrast, when different formulations of bioplastics were introduced, the results showed a significant increase: Sea FN°1 (0.12); River FN°1 (0.20); Sea FN°2 (0.17); River FN°2 (0.24); Sea FN°3 (0.22) and River FN°3 (0.30). According to Perojo-Bellido de Luna et al. (2022), the following classifications are established for biodegradability based on the BOD_5/COD ratio: if BOD_5/COD > 0.4, the wastewater is highly biodegradable; if 0.2 ≤ BOD_5/COD < 0.4, it is moderately biodegradable; and if BOD_5/COD < 0.2, it is classified as poorly biodegradable or non-biodegradable.

When the BOD_5/COD ratio was determined, it was observed that river water exhibited higher biodegradability, being classified as moderately biodegradable. Conversely, although the increases in BOD in seawater with the different bioplastic formulations showed higher results, they were still classified as poorly biodegradable or non-biodegradable, with the exception of Mar F3 (0.22). It is important to note that the only variable altered across all formulations was PVA, suggesting that the amount of this component influences the biodegradability rate of the bioplastic in aquatic environments (Ben Halima, 2016; Elgharbawy et al., 2024). However, this conclusion should be approached with caution due to the limited number of studies addressing this specific relationship.

PVA vs. biodegradability index correlation

Unlike the biodegradation plots, Figure 10 demonstrates a clear positive linear relationship between PVA concentration and the biodegradability index in both aquatic environments. This indicates that an increase in PVA concentration leads to a corresponding increase in biodegradability. The high R^2 values 0.9868 for the marine environment and 1.0 for the riverine environment suggest an excellent fit of the linear model, highlighting PVA concentration as a strong predictor of biodegradability under these conditions. The differences in the slopes of the lines indicate that environmental conditions play a crucial role in influencing the biodegradability of PVA. The higher R^2 value observed in river water suggests lower variability in biodegradability compared to seawater, pointing to a more predictable degradation behavior in the riverine environment. This emphasizes the importance of considering the specific environmental context when evaluating bioplastics, as different ecosystems can significantly alter their degradation dynamics. These findings are consistent with previous studies that have highlighted the impact of environmental factors on bioplastics' behavior (Afshar et al., 2024). Understanding these variations is essential for optimizing the use of bioplastics in diverse aquatic environments.

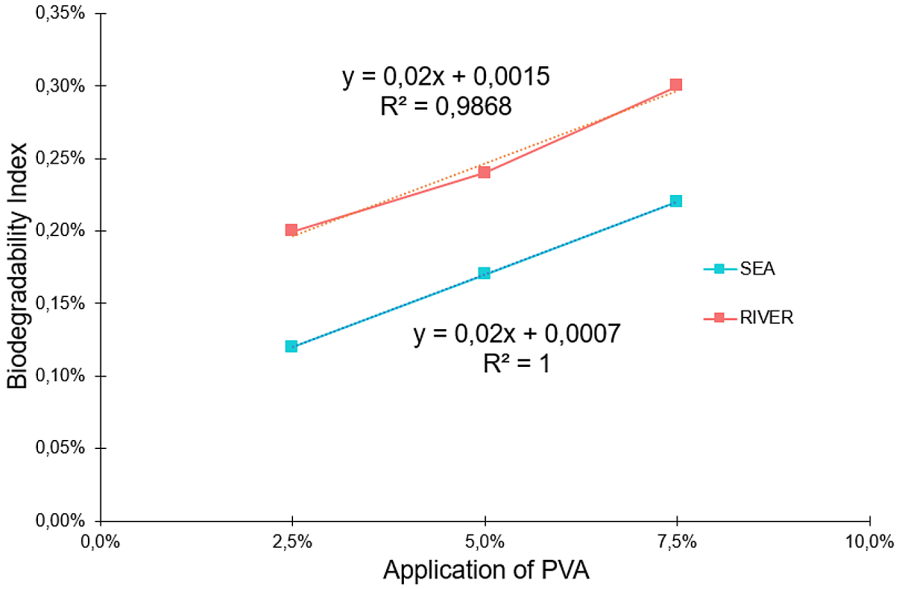

Figure 10. PVA vs. biodegradability index correlation

The study reveals that the bioplastic formulations tested significantly altered key parameters in both river and seawater. These changes underscore the complex interactions between bioplastics and aquatic environments. Additionally, it is important to note that many of the biodegradation test methods reported in the literature lack standardized protocols, leading to highly variable, and at times contradictory, results. This variability complicates the accurate assessment of bioplastics' effectiveness in aquatic environments, as noted by ASTM International (2017) and Lott et al. (2020). The inconsistency in test conditions like temperature, salinity, and material properties makes this problem even more challenging. This highlights the need for more reliable and standardized protocols for biodegradation testing.

CONCLUSIONS

The results demonstrate that bioplastics derived from banana peels exhibit high biodegradability in aquatic environments, making them a promising alternative to conventional plastics for mitigating plastic pollution. Furthermore, the study reveals efficient decomposition of these bioplastics in both river water and seawater, supported by observable morphological changes in the bioplastic films and the active involvement of degrading microorganisms. These findings have significant implications for managing plastic pollution in aquatic ecosystems, underscoring the importance of incorporating biodegradability into the development of sustainable environmental management strategies. The data from this study provides a strong foundation for scientific progress. The high biodegradation rate, combined with the observed morphological changes, supports the potential of these materials to efficiently decompose and reintegrate into the environment. This process helps reduce the negative impact of plastics on aquatic ecosystems and promotes more sustainable practices within the materials industry. However, further research is essential to fully understand the biodegradation mechanisms of bioplastics and their long term effects on aquatic ecosystems. Complete decomposition may take time and could depend on various factors, such as the precise chemical composition of the materials and the presence of degrading microorganisms in the aquatic environment.

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