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Physical-mechanical analysis of plastic materials for the design of recycled furniture in Guayaquil

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Resumen— La producción anual de residuos plásticos en Guayaquil se ha duplicado en apenas dos décadas, y ahora se generan alrededor de 39 mil toneladas de residuos plásticos. En este contexto, la industria de la construcción debe avanzar hacia el desarrollo de nuevos materiales más sostenibles elaborados bajo criterios de economía circular. En este trabajo se ha realizado una caracterización físico-mecánica de composites de tres muestras de plásticos, residuos de polietileno de alta densidad (PEAD), sustituyendo un 2,5-5,0-7,5-10,0% en volumen de la materia prima original. Los resultados muestran cómo la incorporación de estos residuos plásticos mejora la resistencia al agua de 3 tipos de materiales sin aditivos, además de producir una disminución de la conductividad térmica y una mayor resistencia al impacto. Este resumen profundiza en la exploración de vías para la evaluación de polímeros en materiales ecológicos, arrojando luz sobre sus atributos, usos y obstáculos inminentes.

La evaluación de biopolímeros implica un escrutinio exhaustivo de sus características físicas, mecánicas, térmicas y de barrera, junto con su comportamiento de degradación y compatibilidad con otros materiales. Técnicas como la reología, la espectroscopia, la microscopía y el análisis térmico asumen papeles cruciales en la caracterización de biopolímeros y la determinación de su idoneidad para diversas aplicaciones. Los biopolímeros descubren aplicaciones en una amplia gama de sectores, incluidos el embalaje, el textil, la automoción, la electrónica y la industria biomédica. Su biodegradabilidad intrínseca, biocompatibilidad y baja huella de carbono los hacen atractivos para multitud de usos. Además, los biopolímeros se pueden adaptar para exhibir propiedades específicas, lo que permite la personalización para cumplir requisitos precisos. A pesar de su potencial, varios desafíos impiden la aceptación generalizada de los biopolímeros. Estos desafíos abarcan la disponibilidad restringida de materias primas, costos de producción elevados, propiedades mecánicas inferiores en comparación con los polímeros tradicionales y la necesidad de técnicas de procesamiento mejoradas.

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Además, la gestión de productos a base de biopolímeros al final de su vida útil y la eliminación de residuos de biopolímeros requieren una consideración meticulosa para garantizar la plena realización de sus ventajas medioambientales. La resolución de estos desafíos exige la cooperación interdisciplinaria entre investigadores, formuladores de políticas, partes interesadas de la industria y consumidores. El desarrollo de metodologías de procesamiento innovadoras, tecnologías de reciclaje eficientes y cadenas de suministro sostenibles es indispensable para desbloquear todo el potencial de los biopolímeros y garantizar su perfecta integración en materiales ecológicos.

La evaluación de biopolímeros en materiales sostenibles implica una estrategia multifacética que abarca la caracterización integral, la personalización para aplicaciones específicas y la superación de los desafíos existentes. Al mejorar nuestra comprensión de los atributos de los biopolímeros y perfeccionar sus procedimientos de fabricación y eliminación, podemos trazar un rumbo hacia un futuro más sostenible y respetuoso con el medio ambiente.

Por otro lado, se ha comprobado que a medida que aumenta el porcentaje de materia prima reciclada añadida, la resistencia mecánica a la flexión y compresión disminuye, llegando a producirse fractura por falta de cohesión entre la matriz y el residuo. El objetivo del estudio es establecer un diseño de materiales aplicados al mobiliario de espacios públicos como potenciador del desarrollo sostenible del territorio al reducir la contaminación y contribuir a la autoconstrucción y generación de prototipos de diseño. Así, los resultados confirman la viabilidad de estas materias primas para ser utilizadas en el desarrollo de prototipos, especialmente en el diseño de muebles prefabricados y autoensamblados.

Palabras clave: Análisis de materiales, espacios públicos interactivos, desarrollo sustentable, ordenamiento territorial, diseños de mobiliario.

***Abstract*—** The annual production of plastic waste in Guayaquil has doubled in just two decades, and now around 39 thousand tons of plastic waste is generated. In this context, the construction industry must move towards the development of new, more sustainable materials made under circular economy criteria. In this work, a physical-mechanical characterization of composites of three cain of plastics, high-density polyethylene waste (HDPE) has been carried out, replacing a 2.5-5.0-7, 5-10.0% by volume of the original raw material. The results show how the incorporation of these plastic waste improves the water resistance of 3 types of materials without additives, in addition to producing a decrease in thermal conductivity and greater impact resistance. This brief delves into exploring avenues for evaluating polymers in green materials, shedding light on their attributes, uses, and looming obstacles.

The evaluation of biopolymers involves exhaustive scrutiny of their physical, mechanical, thermal and barrier characteristics, along with their degradation behavior and compatibility with other materials. Techniques such as rheology, spectroscopy,

microscopy and thermal analysis assume crucial roles in characterizing biopolymers and determining their suitability for various applications. Biopolymers find applications in a wide range of sectors, including packaging, textiles, automotive, electronics and the biomedical industry. Their intrinsic biodegradability, biocompatibility and low carbon footprint make them attractive for a multitude of uses.

Additionally, biopolymers can be tailored to exhibit specific properties, allowing customization to meet precise requirements. Despite their potential, several challenges prevent the widespread acceptance of biopolymers. These challenges encompass restricted availability of raw materials, high production costs, inferior mechanical properties compared to traditional polymers, and the need for improved processing techniques. Furthermore, the management of end-of-life biopolymer-based products and the disposal of biopolymer waste require meticulous consideration to ensure full realization of their environmental benefits. Resolving these challenges requires interdisciplinary cooperation between researchers, policymakers, industry stakeholders, and consumers. The development of innovative processing methodologies, efficient recycling technologies and sustainable supply chains is essential to unlock the full potential of biopolymers and ensure their seamless integration into green materials.

The evaluation of biopolymers in sustainable materials involves a multifaceted strategy that encompasses comprehensive characterization, customization for specific applications, and overcoming existing challenges. By improving our understanding of the attributes of biopolymers and refining their manufacturing and disposal procedures, we can chart a course toward a more sustainable and environmentally friendly future.

On the other hand, it has been proven that as the percentage of recycled raw material added increases, the mechanical resistance to bending and compression decreases, leading to fracture due to lack of cohesion between the matrix and the waste. The objective of the study is to establish a design of materials applied to furniture in public spaces as an enhancer of the sustainable development of the territory by reducing pollution and contributing to self-construction and generation of design prototypes. Thus, the results confirm the viability of these raw materials to be used in the development of prototypes, especially in the design of prefabricated and self-assembled furniture.

Keywords: Material analysis, interactive public spaces, sustainable development, territorial planning, furniture designs.

I. INTRODUCTION

The development of urban peripheries in Guayaquil, Ecuador, follows a pattern like that of urban expansion in many other Latin American cities since it develops emerging from the need for the progressive search for urban living and to generate a process of radical settlement and appropriation [1]. This radical growth has experienced significant growth and urbanization in recent decades as opportunities to obtain dignified housing through housing plans [2], urban peripheries are activated, they become centers of development influenced by several factors, including demographic growth, the economic opportunities and the infrastructure development that is planned by the inhabitants; which, as an effect, is developed without urban planning consistent with the preparation and projection of a territory that is suitable and whose risks are minimal.

Polymers are made of covalently bonded monomers through various chemical processes whereas biopolymers are a specific section of polymers that are made by living beings using enzymatic pathways. Biopolymers are defined as the polymers developed by or derived from the cells of living creatures that include plants, microbes or bacteria. This means that the primary and major source of biopolymers is renewable and biodegradable [1]. These include plant resources (wheat, maize, yams, potatoes, barley etc.), animal resources (cattle's), marine resources (lobster, fish, shrimp etc.), and microbiological resources (yeasts, algae, and fungus). They contain monomers i.e., single unit bonding covalently to form a bigger chain of molecules. These biopolymers have found scope in many industrial applications that include food packaging, medicines, and cosmetics [2]. Biopolymers have an evenly distributed set of molecular mass that looks like a long chain of worms under a microscope. Biopolymers, due to their easily availability, and abundance presence, biocompatibility and promising characteristics including ecological and economic concerns hence employed for applications that include selective and sensitive gas as well as vapor sensors. These properties have made them one of the satisfactory options for industrial water waste treatment. Below **Fig. 1** lists the major resources of natural biopolymers.

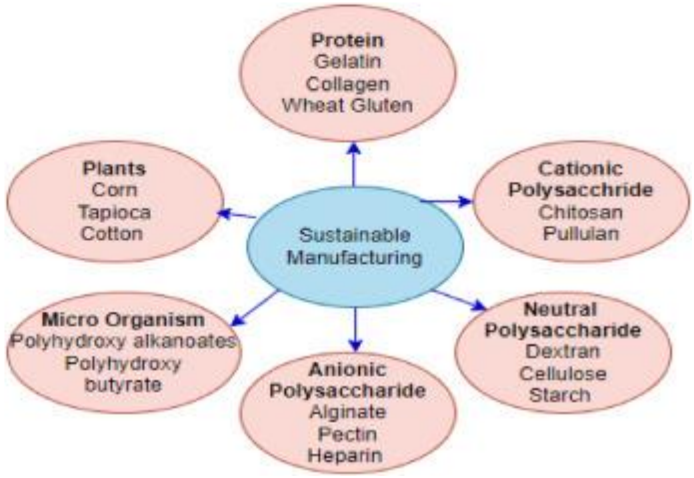

Fig. 1. Description of plastic polymers in manufacturing industry. Notes: Prepared by the authors.

Efforts to manage the development of urban peripheries in Guayaquil will need to focus on sustainable development, community participation and inclusive planning to ensure that the city's growth benefits all residents and maintains its cultural value and environmental identity [3]. Urban planning at the outset and local governance at a development stage play a crucial role in achieving this balance.

Plastic waste worldwide has achieved an abrupt peak growth until 2022 due to high consumerism towards the plastic industry, largely due to the emission of plastic bottles, bags and containers that currently together generate 150 million metric tons of this amount of waste, only 9% are recycled according to the OECD Global Plastic Outlook Report [4].

Plastics have 3 variants that contribute to better recycling when incorporated into construction [5]. Firstly, there is PET (Polyethylene Terephthalate), which is easy to recycle since you can obtain crushed shavings, synthetic fibers. Casings and strips of minimum thicknesses between 0.2 and 0.6 centimeters can be easily incorporated into a dosage, with lightening, waterproofing properties, and medium bending resistance [6].

HDPE (High Density Polyethylene), a material found in spherifications and small quadrants no larger than 0.01 centimeters in height and width, this material has interesting properties of resistance to low and high temperatures [7], absorbent and with high resistance to bending and compression. PVC (Polyvinylchloride), a material with an intermediate level of degradation, is rarely used since its recycling process [8] involves more complex and expensive processes that mean that this material is only found in spherifications that are introduced at dosages of construction materials generate a high flexural strength and a high average compression strength.

II. MATERIAL AND METHODS

2.1. Selection of plastics

The four thermoplastics used in this study are PET, PVC and HDPE these plastics are the most widely used and have a high prevalence in the environment, as they are popular options for single-use plastics, such as beverage bottles and take-out containers [9]–[11]. PVC's properties of high levels of toughness, good heat resistance and being an electrical inductor have made it a favorable material for electronic applications [12]. Proper management of e-waste is becoming a growing problem for many countries, and it is estimated that between 20 and 50 million tonnes of e-waste are produced annually [13]. HDPE is a high-strength thermoplastic [14]. Since PET is derived from a renewable source, its popularity as an alternative to fossil-based plastics has increased, with an estimated production of 190,000 tons by 2019 [15]. This study will focus on PET and HDPE due to their popularity as single-use plastics and high resistance as a material for assembly, PVC, being a continuous source of waste, will be considered for furniture finishes and less tense elements and exposed to specific weight.

2.2. Plastic degradation

A plastic can be described as degradable when it undergoes a significant change in initial properties due to chemical cleavage of the macromolecules forming a polymeric item regardless of the mechanism of chain cleavage i.e. there is no requirement for the plastics to degrade due to the action of naturally occurring micro-organisms. Examples of degradable plastics include oxo-degradable and UV-degradable which break down when exposed to oxygen or light and are primarily oil-based.

i) Biodegradability

Biodegradability can be described as “the degradation of a polymeric item due, at least in part, to cell-mediated phenomena. As a result of the action of micro-organisms the material is ultimately converted to water, carbon dioxide, biomass and possibly methane”. The ability of a polymer to biodegrade is independent of the origin of its raw material. Instead, it strongly depends upon the structure of the polymer. For example, whilst some bio-based plastics may be biodegradable e.g. poly-hydroxy-alkanoates) others are not (e.g. polyethylene derived from sugar cane). Some polymers degrade in only a few weeks, while others take several months.

In comparison with conventional commodity polymers, biodegradable polymers are niche market materials finding focused applications within a diverse range of market sectors, including Medical Devices: orthopedic, dental, drug release and tissue engineering in Agriculture as mulch films, flowerpots, and encapsulation of fertilizers for controlled release and in packaging: carrier bags, waste bags, food wrapping and containers.

ii) Composability

For a plastic to be considered compostable it must meet the following criteria Biodegradable break down into carbon dioxide, water, and biomass. 90 % of the organic materials is converted into CO_2 within 6 months. Disintegrate after 3 months composting and subsequent sifting through a 2 mm sieve, no more than 10 % residue remains. Eco-toxicity: biodegradation does not produce any toxic material and compost can support plant growth.

Plastic therefore may be degradable but not biodegradable or it may be biodegradable but not compostable (i.e. it breaks down too slowly or leaves toxic residues). The state-of-the-art literature on oil-based polymers focuses on sustainable alternatives and enhanced recycling methods, while microbial polymers are explored for their biodegradability and potential applications in biotechnology and medicine.

No other research was found which shows the synthesis and applications of sustainable materials using oil based and microbial polymers. In addition to this very few studies have used both categorization of biopolymers and their processing for different sustainable materials. The present study would be providing a roadmap to new studies regarding the selection of different bio polymers on various unexplored factors in the direction of various sustainable materials used in numerous applications.

2.3 Role of biopolymers in bioplastics

Bioplastics provide a more sustainable answer to the world's plastic pollution problem than traditional petroleum-based plastics. Bioplastics may be created from renewable resources such as maize starch, sugarcane, vegetable fats and oils, and they can be biodegradable or compostable, lowering their environmental effect [6]. Bioplastics are classified into three types: bio-based, biodegradable, and compostable. Biodegradable and non-biodegradable bio-based polymers are manufactured from renewable resources. Microorganisms may degrade biodegradable polymers into natural substances such as water, carbon dioxide, and compost. Compostable plastics are a type of biodegradable plastic that may be broken down in industrial composting facilities and disintegrate into natural elements over time.

Bioplastics have a wide range of uses, including the packaging, agricultural, automotive, and electronics sectors. Biodegradable and compostable polymers are extensively utilized in packaging applications such as food packaging and shopping bags to decrease waste and environmental impact. Bioplastics are also utilized in agriculture for mulch films, plant containers, and biodegradable insecticides. Bioplastics are utilized in the car industry to reduce weight and enhance fuel efficiency in interior components such as dashboards and door panels. Lastly, in the electronics business, bioplastics are employed for electrical components and casings [9]. Yet, there are significant difficulties in the development and usage of bioplastics. One problem is that the cost of manufacture is often greater than that of traditional petroleum-based polymers. Another difficulty is the lack of readily available specialized composting facilities for biodegradable plastics. Generally, bioplastics are a more environmentally friendly alternative to standard petroleum-based plastics. While obstacles remain in their manufacturing and usage, continued research and development is projected to lead to additional advancements in bioplastics' performance and cost-effectiveness.

2.4 Categorization of biopolymers

2.4.1 Based on type of chemical composition

• Sugar-based polymers: These include starch or sugar as input material for developing biopolymers. Lactic acid polymers are also used to create lactose from potato, maize etc. These can be developed by blowing, extrusion and vacuum forming injection.

• Starch based polymers: Starch here acts as a natural polymer and contains glucose. These are found in plant tissues and found in tapioca, maize, wheat, and potatoes.

• Cellulose based biopolymers: It is made up of glucose having natural sources like cotton. It is employed for packaging. These are found in natural resources including walls, cotton, corn, and wheat etc.

• Synthetic Material: Polymers that are degradable can be manufactured from synthetic materials that include petroleum. These are compostable and environmentally friendly though they are obtained from synthetic materials.

2.2. Based on type of monomeric unit

• Polysaccharides: It includes carbohydrate chains that may be linear or branched. For example: cellulose, chitosan, chitin, starch etc. Polysaccharides: Glycosidic linkages are used to combine the monosaccharides to get polysaccharides.

• Proteins: Amino acids combine to form proteins. For example: fibrin, gelatin, gluten, collagen etc.

• Polynucleotides: Long polymer chain of nucleic acid made from 13 or a few more monomeric units. For example: DNA, RNA etc

2.3. Based on the type of origin

• Natural Polymers: These are biosynthesized by living organisms.

• Synthetic Polymers: These are made of renewable materials including polylactic acid that are degradable in nature.

• Microbial: These are produced by microorganisms.

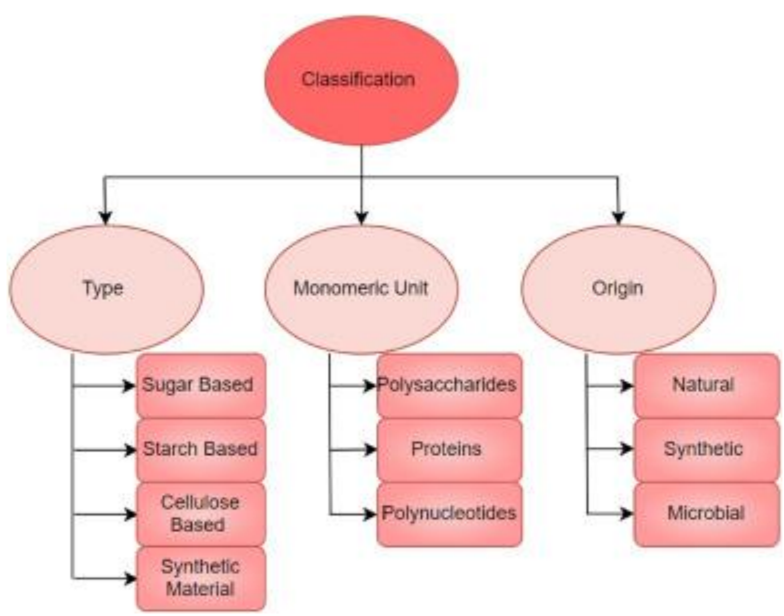

Fig. 2. Types of biopolymers. Notes: Prepared by the authors.

2.2. Sample preparation

The method used an experimental study with characteristic samples be 1 mm to 2 mm thick. Samples of PET, HDPE, and PVC were compacted in molds in two different shapes: dog bone and rectangular (40 mm × 20 mm). The dog bone shape was used for tensile testing and the shape profile was replicated from the ASTM D638 type IV shape, measuring 115 mm long and 19 mm wide. Rectangular plastic samples were used for all other testing procedures. The PVC samples were waterjet cut from a 1mm sheet obtained from RS Pro Components (cutting and pre-filing machine) into the shapes indicated above. The plastic samples were washed with Milli-Q water to remove any residue from the surfaces. Humic acid and reagent grade sodium chloride. A UVA weathering chamber was constructed in the laboratory using two 10 W-UVA-340 lights which produced light at a wavelength of 340 nm to simulate natural sunlight. A test of the final physical mechanical analysis of the materials that can be used for the development of furniture that obtains less degradation and longer useful life with respect to the environment will be carried out.

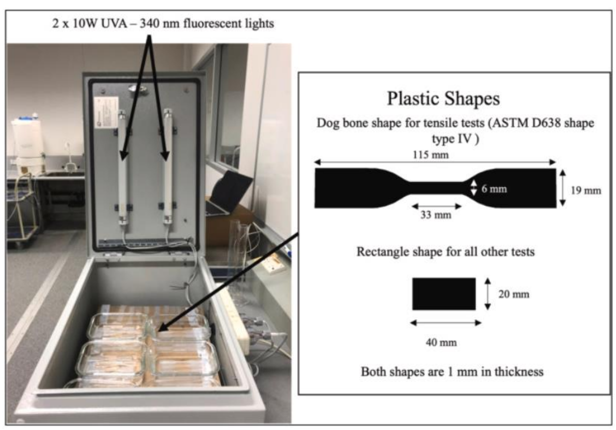

Fig. 3. UVA physico-mechanical degradation experimental in 3 plastic samples. Notes: Prepared by the authors.

III. RESULTS

3.1. Water absorbance

The change in the weights of the PET, HDPE, and PVC samples after being subjected to simulated environmental degradation was carried out using precision scales (1000 × 10-1 g) and are shown in Fig. 2. Changes were observed of negligible weight at baseline in the three types of plastic exposed to air PVC and HDPE observed minor changes in all simulated aquatic environments, illustrating their inability to absorb moisture from their environments due to their hydrophobicity. The weight of PET was found to increase when submerged in Milli-Q aquatic environments, particularly in the presence of salt or humic acid. The largest weight change for PET (5.27 ± 1.58%) and PLA (8.62 ± 2.29%) occurred in the presence of humic acid and NaCl, respectively. It is worth reiterating that water absorption also was confirmed by the change in the hydroxyl group represented in the FTIR spectra.

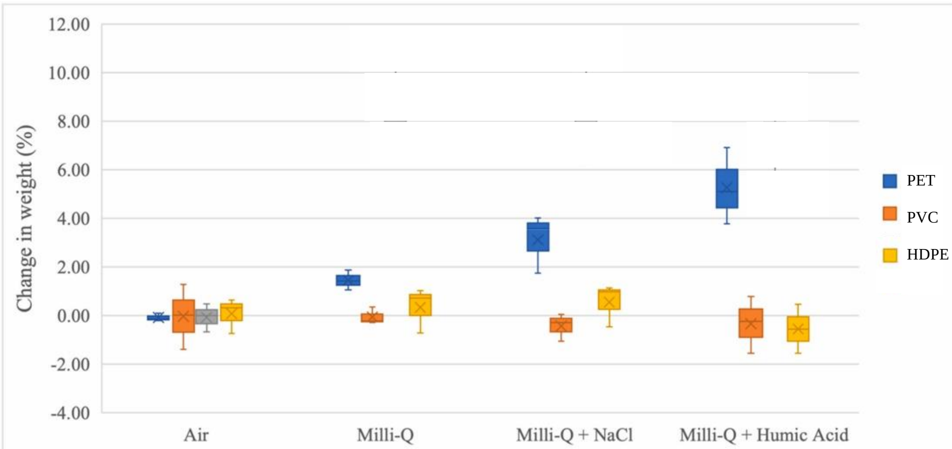

Fig. 4. Change in weight of plastic samples after being exposed to different simulated environmental conditions for 28 days. Error bars are showing mean, median, and standard deviation of three samples. Notes: Prepared by the authors.

3.2. SEM Analysis

SEM (Scanning Electron Microscopy) analysis was used to visually inspect the change in surface morphology of the plastic samples after being exposed to UVA radiation for 28 days in different simulated environments. The changes in surface morphology of PET and PVC samples can be seen in Fig. 3, Fig. 4; respectively. The results for the HDPE samples do not illustrate notable changes in their surface morphology. It was evident that the environment greatly influenced the degree of surface degradation that occurred, with samples subjected to aerial environments showing the greatest change in surface morphology.

Cracks, flakes, prominent ridges, and deformations were observed on the surface of PET and PVC samples after subjecting them to the tested conditions. When PET samples were immersed in Milli-Q aquatic environments, some level of surface morphology protection was observed. PET has been shown to absorb water from its environment, which can potentially provide some level of surface protection against UVA irradiation. PVC, on the other hand, is naturally a hydrophobic material [16] and was observed to not absorb moisture from its environment. The lack of hydroxyl group in the PVC samples may explain the degradation that was observed on the surface of all the samples that were immersed in the Milli-Q environments.

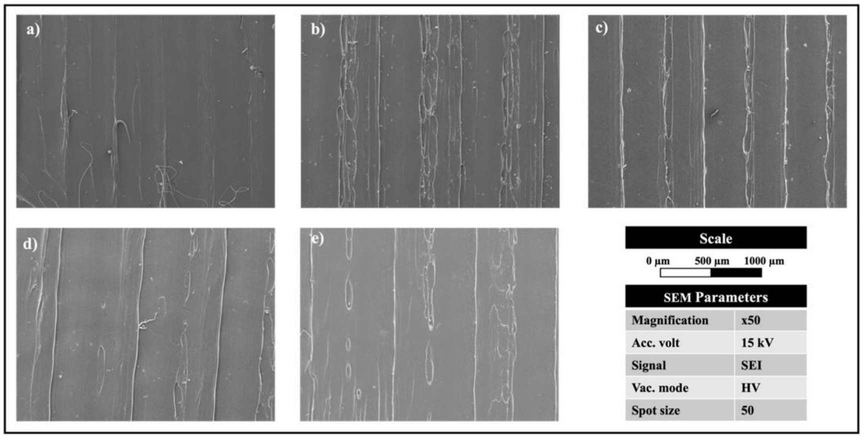

Fig. 5. SEM images of the surface of PET samples after being exposed to different environmental conditions for 28 days. a) control; b) air; c) Milli-Q water; d) Milli-Q + NaCl; e) Milli-Q + humic acid. More prominent ridges were seen in all SEM images when compared to the control sample illustrating the surface degradation that occurred due to environmental degradation. Notes: Prepared by the authors.

The results obtained through SEM analysis not only show how polymers degrade differently under the same conditions tested, but also how different polymers may have a greater potential to release microplastics into the environment. Comparison of Figures 3 and 4, which are the results of samples placed in a simulated ocean environment, shows that the PVC surface has higher degradation levels than PET. PVC may pose a greater threat to ocean life because it breaks down into smaller fragments and is mistaken for food [17]. Ocean microplastic pollution has been found to affect the health and development of marine life [18]–[20] and potentially become a vector of bacteria and resistant genes [21].

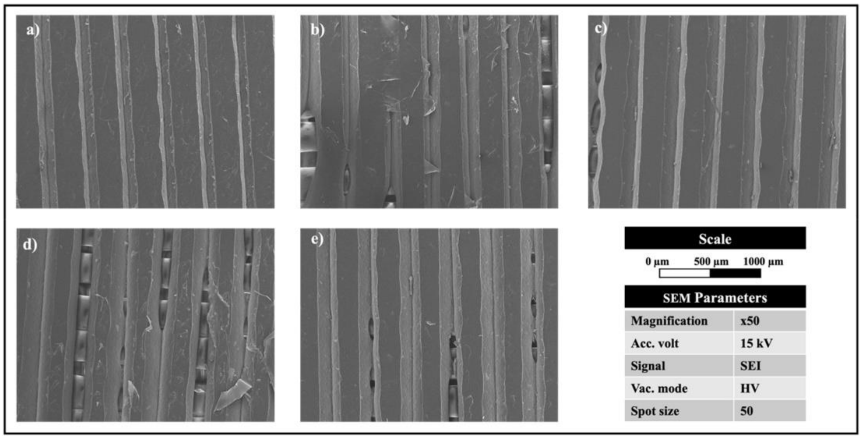

Fig. 6. SEM images of the surface of PP samples after being exposed to different environmental conditions for 28 days. a) control; b) air; c) Milli-Q water; d) Milli-Q + NaCl; e) Milli-Q + humic acid. Flakes, cracks, and separation were seen on PP samples that were exposed to 28 days of environmental conditions when compared to the control sample. Notes: Prepared by the authors.

IV. DISCUSSION

Previous research that has used SEM analysis to examine the recyclability of discarded plastics has yet to discuss the implications of degraded surface morphology and the potential to contaminate the recycled product with unknown contaminants [22]. The cracks and holes that can be examined in Figures 3 and 4 are potential places for contaminants to collect and accumulate [23]. If collected and recycled, without proper and thorough cleaning, these contaminants can be transferred to the new recycled product. This is an important factor that has so far been overlooked in the literature and should be considered when determining the feasibility of recycling waste plastics.

V. CONCLUSION

This study has shown that environmental conditions play an important role in the level of plastic degradation with respect to tropical climates such as those of the city of Guayaquil. Organic compounds dissolved in water together with exposure to UVA rays can generate notable changes in the physical and mechanical and even chemical properties of plastics. The properties of PET and PVC degraded to a level where recycling of the plastics was less suitable. In contrast, the chemical, mechanical, and physical properties of HDPE were not affected during the 28-day experimental period, indicating its recycling potential under similar exposure conditions.

Based on the changes that occurred in plastic samples that had been exposed to simulated environments, the findings of this study explored the possibility of giving value to plastics that were once considered waste products and converting them into utilitarian furniture within the public space called interactive due to the self-construction and on-site assembly of plastic pieces. Future research in this area should focus on developing a classification system for plastic collected from the environment so that it can be recycled accordingly and developing standards for the allowable levels of degradation that a plastic must undergo before it is no longer acceptable to the environment recycling.

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