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**HISTORIC AND PRESENT AGRICULTURAL LAND USE AND ITS EFFECTS IN  
PLASTIC DEBRIS IN A SEMI-ARID AGRICULTURAL REGION OF SOUTHERN  
PUERTO RICO**

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## Abstract

Plastic pollution has reached global proportions due to its durability, affordability, and widespread use of plastics. However, studies on the impacts of plastic particles in soil ecosystems remain scarce. Plastics covers are commonly used in arid and semi-arid regions and historically applied in agricultural soils to regulate temperature, maintain humidity, and suppress weed growth. Over time, wind, heavy machinery, and UV radiation degrade plastic covers into particles, contributing to soil pollution and potentially disrupting natural soil processes. At Finca Atabey, a multi-crop farm in Santa Isabel, Puerto Rico, semi-arid south of the island, both non-biodegradable and biodegradable plastics are employed in crop production. This study evaluated if long-term plastic use generated quantifiable plastic debris in soils hosting perennial (avocado) and annual (pumpkin) crops with differing plastic use histories and soil management practices. We hypothesized that Finca Atabey's soils would exhibit high plastic concentrations due to long-term non-biodegradable plastic use, with pumpkin fields exhibiting higher concentrations, greater size variability, and minimal depth variation. To test this hypothesis, soil samples were collected from each crop at two depths to quantify plastic pollution, using sieves, magnifying tools, and precision lab tweezers. Student's t-tests, histograms, and box plots were constructed to analyze and visualize data. Results showed significant differences in the quantity of microplastics between crops ( $p$ -value  $< 0.05$ ;  $t = 4.03$ ), with the relative contribution of non-biodegradable microplastics being higher in the pumpkin field ( $p$ -value  $< 0.05$ ;  $t = 4.70$ ) and highlight the effects of plastic use and soil management on the fragmentation and incorporation of plastics to agricultural soils. Understanding pollutant dynamics in agroecosystems can inform strategies to reduce plastic concentrations, and therefore, safeguard soil health, crop quality, and overall ecosystem integrity.

*Keywords:*

*Legacy plastics, soil ecosystems, crop management, plastic pollution, microplastics*

## **Dedication**

To my parents and brother, for loving me unconditionally; and to my grandparents and my uncle, who watched over me from heaven and gave me the strength to keep moving forward.

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## Introduction

Plastic pollution in the environment has reached exceptionally high levels due to its durability, affordability, and widespread use in commerce, industry, and agriculture (Sa'adu & Farsang, 2023). From 2010-2020 there were 3,815 publications related to microplastic debris, of which 7.3% are related to soil (Kim *et al.*, 2020). This points toward a notable lack of studies focusing on the impacts of plastic particles in soil ecosystems. The use of plastic covers is a common agricultural practice for improving yields and crop quality, and water use efficiency (Steinmetz *et al.*, 2016). The materials Polyethylene (PE) films and Polypropylene (PP) of various thicknesses are the most used materials in agricultural soils, made to last for up to a decade (Bertling *et al.*, 2021). As these plastics degrade, they break down into various sizes of plastic debris, contributing to soil pollution (Yu *et al.*, 2022). Therefore, the long-term presence of plastic debris in agricultural soils raises concerns about their cumulative effects, potentially altering soil's natural processes.

Agricultural plastics were developed in the 1940's (Shah & Wu, 2020), and have been used to regulate temperature, maintain humidity and decrease weed growth in agricultural fields, capitalizing on their beneficial properties in low precipitation sites. In arid and semi-arid regions, the use of plastic covers has become the standard (Van Der Meulen *et al.*, 2006). The global use of agricultural plastic films accounted for 4.4 million tons in 2012 and was expected to grow to 7.4 million tons in 2019 (Sintim and Flury, 2017, cited by Jansen *et al.*, 2019). In Puerto Rico, *April Agro* introduced the use of plastic covers and drip irrigation in the semi-arid southern region in the 1970s after the abandonment of the sugar cane production (Segarra, 2022).

Finca Atabey, a multi-crop agricultural farm, located in Santa Isabel, was established in 2000. Plastic covers were initially used in the establishment of the perennial crop rows, in 2003. For annual crops, plastic cover is methodically used, as it is systematically and intentionally

applied over the soil to regulate temperature, maintain humidity and decrease weed growth (Van Der Meulen *et al.*, 2006). Since 2023, biodegradable plastics replaced the nonbiodegradable plastics in the annual crop rows. These bio-based plastics are materials derived fully or partially from plant-based resources (e.g., corn, beet sugar, sugarcane, cellulose) that can be decomposed rapidly by microorganisms' fungi and bacteria into elements found in nature (Campanale, 2023).

The historical reliance on non-biodegradable plastics in agricultural sites with low precipitation has raised serious concerns about the potential negative impacts of plastic concentrations on soil health. Over time, wind, heavy machinery, or UV irradiation are likely to disintegrate parts of the covers into macro, meso and microplastic debris (Scarascia-Mugnozza *et al.*, 2011). Mechanical tillage in soils containing leftover plastic can integrate plastic particles into various soil layers, contributing to soil pollution with plastic debris (Ghimire *et al.*, 2020). Plastic debris can significantly affect crop growth and soil health by reducing crop yield, water use efficiency, germination, plant height, root length, and plant biomass (Gao *et al.*, 2022). Furthermore, large amounts of residual plastic mulch films can alter soil structure by reducing rainwater and irrigation infiltration, which negatively impacts the soil's water-holding capacity and can induce anoxia (Qi *et al.*, 2020). Some plastic fragments may create channels that facilitate water movement and evaporation, reducing plants' water uptake for critical processes in crop production (Tang, 2020), becoming especially relevant under present and future climate change and regional climate variability in the Caribbean (IPCC, 2022).

The notable lack of studies focusing on the impacts of plastic debris in agricultural soils in semiarid regions, becomes highly relevant for regions where plant-water dynamics depend on soil water retention and availability due to sporadic pulsing rainfall and high evapotranspiration. We posit the following questions: 1) Does the long-term use of plastics result in a quantifiable legacy

of plastic debris in the soil? 2) Do significant differences exist in the quantity and size of plastic debris based on perennial and annual crop row management? 3) Does soil depth influence the quantity and size of plastic particles? To answer these questions, soil samples were collected for two different crop fields, avocado and pumpkin crops, with different management and plastic use history and from two different soil depths. We hypothesized that: soil samples collected from the agricultural field in Finca Atabey in Santa Isabel, Puerto Rico, will demonstrate a high concentration legacy of plastics from different sizes due to its long history of non-biodegradable plastic use. Additionally, the pumpkin field will exhibit higher concentrations and greater variability in plastic sizes due to more frequent plowing and plastic use, as it is managed as a warm-season annual crop. However, at the pumpkin field, there will be no significant differences in the variability in concentration and sizes of plastic particles at different depths, since annual tillage is carried out, incorporating all soil layers from 0 to 15cm. As for the avocado field, the more superficial soil layers will demonstrate a higher concentration and variability of sizes, since it is being subjected to wind and water erosion, that transport plastic particles from multiple sources. Taking this into account, studying pollutant dynamics in agroecosystems will generate management recommendations to decrease plastic concentrations, effectively producing high-grade food and reducing pollutant impacts on soil-plant dynamics and human health.

## Methods

### *Study Site-*

Sampling took place in Finca Atabey (17° 59' 47" N, 66° 24' 36" W), a multi-crop agricultural field located in Santa Isabel, southern municipality in the semi-arid region in Puerto Rico (Figure 1). Precipitation data indicate that the farm receives approximately 835 mm of rainfall annually (Ortiz-Carrión, 2021). The rainfall is erratic, pulsating, and discontinuous (Ortiz-Carrión, 2021). On average, months in Santa Isabel have more than 20 dry days (Ortiz-Carrión, 2021). Santa Isabel municipality is known for having land use changes, such as changes in crop production, and soil management techniques. Until the 1970's, sugar cane was produced in Santa Isabel and Finca Atabey. This crop was abandoned due to the diversification of the Puerto Rican agricultural product because of the industrial development on the island and was replaced with fruit and vegetable crops (Ortiz-Carrión, 2021). April Agro, in the 1980's, introduced the use of plastics covers and drip irrigation in the semiarid region of Puerto Rico (Segarra, 2022). The farm soils are alluvial soils, specifically, Mollisols: dark, fertile soils with high organic carbon content (Ortiz-Carrión, 2021). There are two soil types series: San Anton series, characterized as fine-loamy, mixed, superactive, isohyperthermic Cumulic Haplustolls, formed from clay loam soils developed in alluvium weathered from volcanic rock and limestone (NCSS, 2006); and the Jacaguas series, classified as loamy-skeletal, mixed, superactive, isohyperthermic Fluventic Haplustolls, originating from clay loam soils in moderately fine-textured stratified sediments derived from volcanic rock and limestone (NCSS, 2000). However, this study will focus only on the Jacaguas soil type (Ortiz-Carrión, 2021). Plastic covers, in Finca Atabey, were initially used in the establishment of the perennial crop rows, like avocado trees. For annual crops, such as pumpkin crops, plastic covers are methodically used, as it is systematically and intentionally

applied over the soil to regulate temperature, maintain humidity and decrease weed growth (Van Der Meulen et al., 2006). Since 2023, biodegradable plastics replaced the non-biodegradable plastics in the annual crop rows (Figure 2b). Tillage is performed annually, incorporating the soil to depths of 30 cm.

#### *Sampling design-*

To study our questions, 10 soil samples were collected from two soil depths, 0-15 cm and 15-30 cm, for two different crop fields: avocado and pumpkin field. In total, 40 soil samples were analyzed to search the concentrations of macro, meso, and micro-plastics. Each soil sample was sealed in identified geological sampling bags, placed in a refrigerated cooler, and taken to the laboratory, where all samples were stored in a forced air oven at 60 °C for a minimum of 42 hours to dry. After this time, the soil samples were weighted, to obtain the soil weight with plastic debris. Each dried sample, individually, was transferred through sifters with meshes of various sizes, 4.75 mm, 2.00 mm, 1 mm, and 0.500 mm, where macro ( $\geq 25$  mm), meso ( $< 25$  mm to  $\leq 5$  mm), and micro-plastics ( $< 5$  mm to  $\leq 1$  mm) sizes were determined (GESAMP, 2016; Hanvey et al., 2017, cited by Fakour et al, 2021). Magnifying tools and precision lab tweezers were used to carefully extract plastic particles collected in the 4.75 mm, 2.00 mm, and 1.00 mm sieve meshes (Figure 3). These particles were placed in labeled bags according to its sieve size for subsequent quantification. For plastic particles discernible without magnification, a ruler and a manual caliper were used to determine the size, depending which method is more appropriate to use due to the variability of sample sizes. Each sample collected of plastic particles from each sifter was weighted to determine the percentage of contribution of plastic debris per soil sampled. Given the historical use of both biodegradable and non-biodegradable plastics in the crop fields, each sample was analyzed to determine its plastic type. Biodegradable plastics were identified by their lighter, white

appearance, while non-biodegradable plastics were characterized by a darker color, black appearance. Additionally, the plastic samples for each type were weighed to assess their contribution to the overall plastic debris in the soil samples.

#### *Statistical Analysis-*

Statistical analyses were carried out using JMP® Pro 18 Statistical Package and RStudio®. To analyze the data, descriptive, inferential, and exploratory analyses were used, based on parametric and non-parametric tests. Histograms and box plots were used to determine total and differential quantities of microplastics based on crops and soil depth. T- tests were also performed to analyze if significant differences exist in the quantity and size of plastic debris based on perennial and annual crop row management and depth.

## Results

### *Legacy of plastic debris in the soil*

The long-term use of non-biodegradable plastic in Finca Atabey's soil results in a quantifiable legacy of plastic debris in the soil (Figure 4). There were significant differences in the total microplastics found per crop type: avocado and pumpkin field (p-value < 0.05; t = 2.86). The legacy of plastic debris in the pumpkin field was significantly higher than that of the avocado field (Figure 5). The percentage contribution of plastic debris per crop type was significantly different (p-value < 0.05; t = 4.70) (Figure 6).

### *Plastic debris quantity and size variations between crop type and depth*

The number of microplastic pieces of all sizes studied (>4.75 mm, 2.00-4.75 mm, and 1.00-2.00 mm), was significantly higher in the pumpkin field compared to the avocado field (p-value < 0.05; t = 2.75) (Figure 7). Both the avocado and pumpkin field had a higher number of microplastic particles in the 1.00-2.00 mm size range at both studied depths: 0 – 15 cm and 15 – 30 cm (Figure 8). Although there were differences in the total quantity of microplastics per crop, no significant differences were found in quantity and size between depths per crop type.

### *Quantity and size variability for plastic type in the pumpkin field*

Significant differences were determined in the percentage of contribution of plastic type: biodegradable and non-biodegradable microplastics for the pumpkin field (p-value < 0.05; t Ratio = -2.45). Non-biodegradable microplastics had higher quantity and size variability in the pumpkin field compared to the avocado field. No biodegradable plastic cover was applied to the avocado field; therefore, no biodegradable microplastic was found in the avocado field. The number of microplastic pieces of all sizes studied from non-biodegradable plastic was significantly higher in the pumpkin field (Figure 9).

## Discussion

Studying the vertical movement, accumulation, and size variability of microplastic particles in agricultural soils becomes extremely relevant, since depending on their shape, type, size, and quantity, microplastics can reduce or increase water-stable aggregates, which leads to changes in soil structures that are important for soil ecosystems functioning (Pérez-Reverón *et al.*, 2022). The historical and current use of plastics in Finca Atabey's soil has resulted in a measurable legacy of plastic debris in the soil. Given the long-term use of non-biodegradable plastic covers in the pumpkin field, as it is annually applied over the soil to regulate temperature, maintain humidity, and decrease weed growth (Van Der Meulen *et al.*, 2006), the legacy of plastic debris was significantly higher than that of the avocado field (22:1). The total number of non-biodegradable microplastic pieces of all sizes studied (>4.75 mm, 2.00-4.75 mm, and 1.00-2.00 mm), was significantly higher in the pumpkin field (1,234 plastic particles), compared to the avocado field (63 plastic particles), as the plastic cover is placed after tillage, and it is left in the field to be incorporated into the soil by fragmentation from mechanical tillage for the next planting. In contrast, in the avocado field, plastic cover was applied once, during the preparation and planting of juvenile avocado trees. There were significant differences in the total quantity of microplastics per crop, while no significant differences were found in quantity and size between depths (0-15 cm and 15-30 cm) per crop type. This finding was contrary to our hypothesis, in which we expected the superficial layers of the soil in the avocado field to contain a higher concentration and size variability of plastic debris.

Microplastics in agricultural soils originate from various sources and follow multiple transport pathways, influencing soil properties and environmental processes (Lwanga *et al.*, 2022). According to the American Society for Plasticulture, plasticulture is “the use of plastic in

agriculture,” which includes but is not limited to plastic mulch films, drip irrigation hoses and tape, row covers, plastic trays, and pots, etc. (Lamont and Orzolek, 2004, as cited by Kasirajan *et al.*, 2012). Plastic films have been determined to be the largest contributors to microplastic contamination in agricultural soils, as they leave behind residues that persist in the environment (Yu *et al.*, 2022). Finca Atabey’s soil is no exception. The historic use of non-biodegradable plastic cover for both annual and perennial crops contributed to a measurable legacy of microplastic in the soil. The total sum (annual + perennial crops) of non-biodegradable microplastics accounted for 89.4% of which 85% was found in the pumpkin soil. The biodegradable input of microplastics, in the pumpkin field, accounted for 10% of the total (Figure 10). The pumpkin field had a higher overall contribution of plastic debris as it is annually subjected to the application of plastic cover and tillage fragmenting and incorporating the remnants in the first 30 cm of soil. High density polyethylene cover degrades at the rate of 100µm/year (Chamas *et al.*, 2020), therefore the legacy of former use will remain in the soil.

The superficial layers of agricultural soils have been found to contain a higher abundance of plastics and microplastics, often caused by plasticulture or the application of plastics in agriculture (Weber *et al.*, 2022). However, mechanical tillage in soils containing leftover plastics can integrate plastic particles into various soil layers (Ghimire *et al.*, 2020). This goes in accordance with what was observed, as the pumpkin field receives more input of plastic cover, there is less variability of plastic debris sizes and quantity between depths. In the avocado field, as the plastic cover and mechanical tillage was applied once, there were no significant difference of size and quantity between depths. Yet, the vertical migration of microplastics in the soil is not only influenced by mechanical tillage, but it can also be influenced by microplastic characteristics, soil physicochemical properties, and biological activity (Luo *et al.*, 2024). For example, Luo *et al.*

(2024), describes that different polymer types display distinct migration behavior, polyvinyl chloride (PVC) and polyethylene (PE) can increase in quantity with depth, while polystyrene (PS) decreases; this is due to difference in density, degradability, and resistance to mobility. In the pumpkin field, non-biodegradable plastics is higher at all sizes, indicating that biodegradable microplastics have a rapid decomposition rate. This suggests that non-biodegradable plastics have a greater capacity to persist in the soil over time. There are main environmental factors that control degradation of biodegradable plastic, such as temperature, moisture, and microorganisms, and these factors vary with climate, weather, soil type, and management practices (Sintim *et al.*, 2020). The management practices in Finca Atabey optimize the degradation of biodegradable plastic cover.

Microplastics, due to their small size and lightweight nature, can have negative impacts on soil ecosystems, agricultural quality, and crop production (Guo *et al.*, 2022). For example, Pérez-Reverón *et al.* (2022), demonstrated that microplastic particles can manipulate crucial biogeophysical processes, harm soil micro- and mesofauna, disrupt microbial activity and affect plant growth. The quantifiable legacy of non-biodegradable plastic debris in Finca Atabey's soil can be used to determine, via experimentation, the effectiveness of the combined effects of photodegradation, to make the degradation faster and easier (Srikanth, 2022). Microplastics can be ingested by soil animals, and induce fake satiety, weak nutrition supply, endocrine disorder, intestinal damages, and even cause mortality (Zhang *et al.*, 2022). Furthermore, soil animals can transport, fragment, and even degrade microplastics, and further influence the fate of plastic debris in the soil (Zhang *et al.*, 2022). Azeem *et al.* (2021), describes that it has been detected the uptake of nano- and microplastics in plants, especially by root hairs. Microplastics cannot enter plant tissues directly, as their large size prevents them too; however, nanoplastics can directly enter the

plant cell walls, potentially reducing crop productivity and plant health (Azeem *et al.*, 2021). This becomes particularly relevant considering our findings, which show a greater presence of smaller microplastics (1.00-2.00 mm). This indicates that plastics do not disappear from the soil but instead continue to degrade into finer particles, increasing the likelihood of their incorporation into crop yields.

There is a notable lack of studies focusing on the impacts of plastic particles in soil ecosystems (Kim *et al.*, 2020), especially in the semi-arid regions of Puerto Rico. Therefore, these findings represent an important contribution to understanding how plastic use in agriculture affects soil health and microplastic accumulation in under-researched environments. In arid and semi-arid regions, the presence of plastic accumulation in agricultural soils becomes pertinent, as they have serious implication on water cycling, especially in the soil's infiltration, water holding capacity, evapotranspiration, and duration of water saturation period (de Souza *et al.*, 2019). The prolonged use and incorporation of non-biodegradable plastic cover in agricultural soils around the world, relies on the fact that it is more affordable for farmers and their removal is time-consuming, requiring hand labor (Kasirajan and Ngouajio, 2012), as they become exceptionally fragile by wind and UV irradiation (Scarascia-Mugnozza *et al.*, 2011). Instead, biodegradable plastic covers represent a better alternative, as they can be destroyed by soil organisms, bioassimilated, or mineralized, but they remain too expensive for agricultural applications (Kasirajan and Ngouajio, 2012). Yet, further research is needed to determine how small plastic particles can be detected in Finca Atabey's soil and whether they are being incorporated into the crop yields. Additionally, there is a pressing need for improved regulations and the development of sustainable strategies to reduce plastic concentrations in agricultural soils, as well as to promote the use of environmentally

friendly alternatives. These efforts are essential to safeguarding soil health, crop quality, and overall ecosystem integrity.

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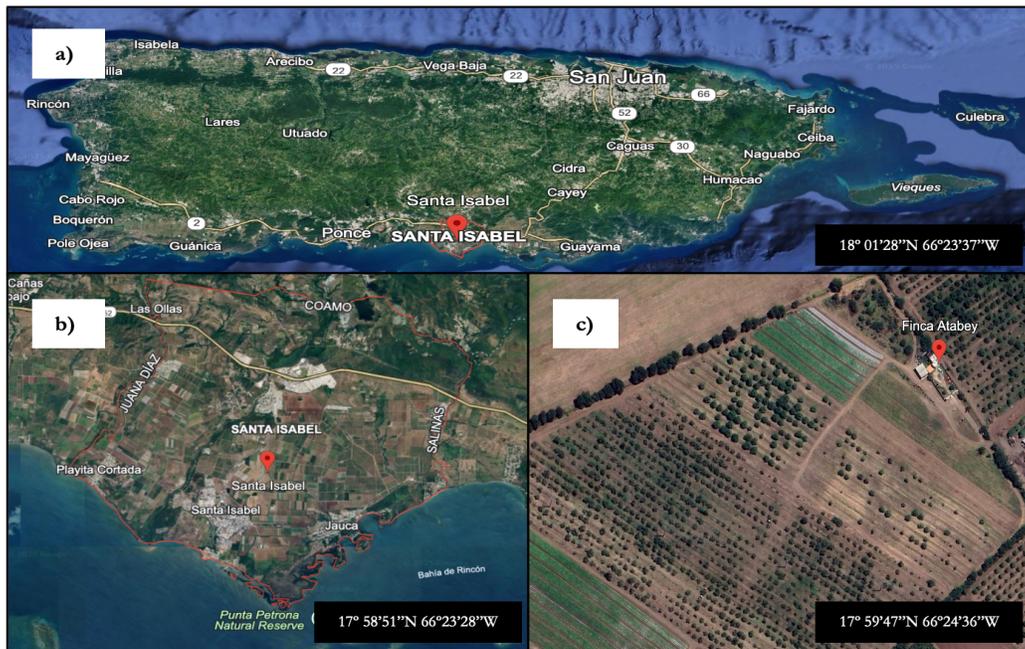
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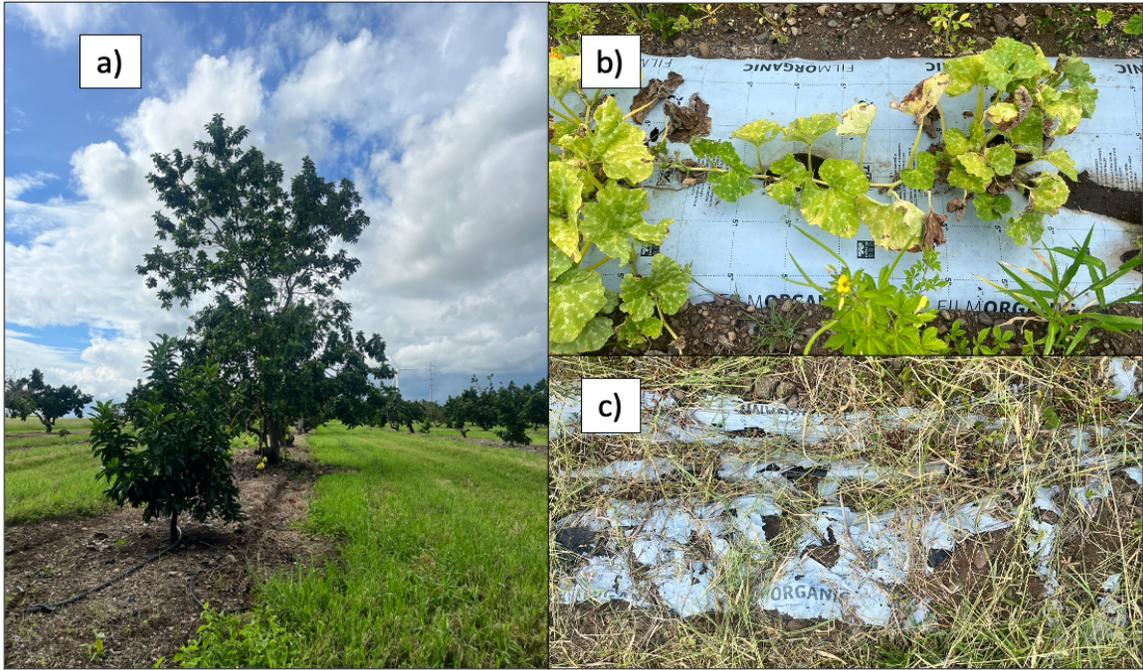
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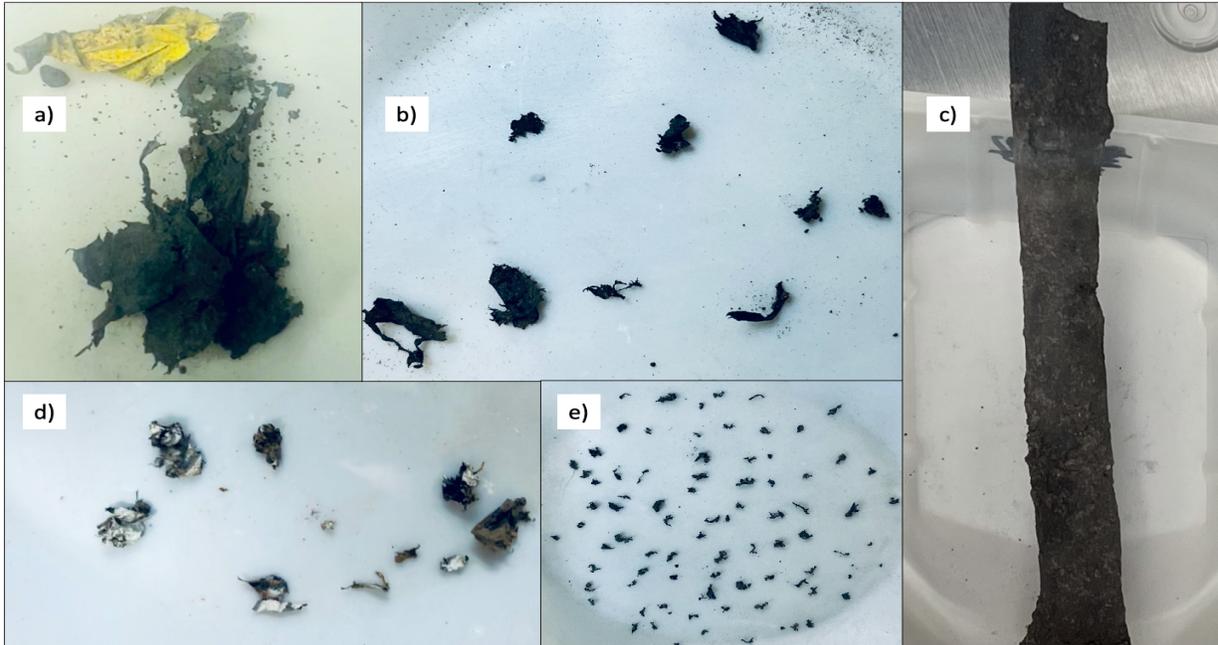
## Figures



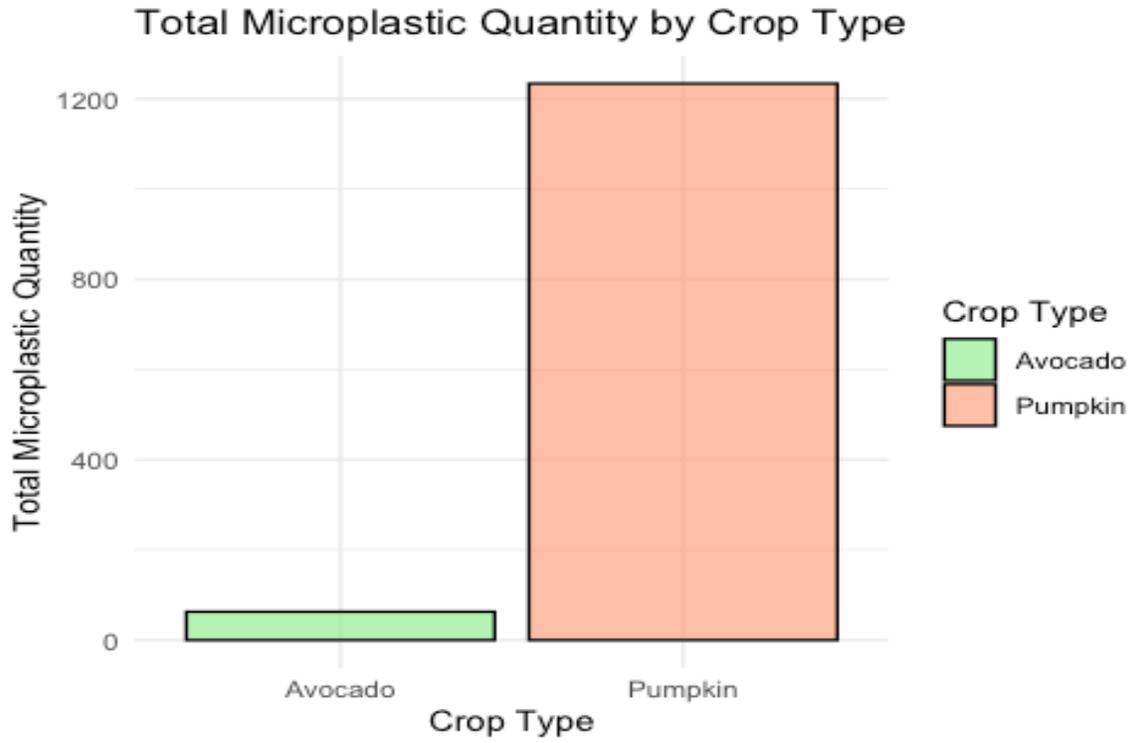
**Figure 1.** Study site coordinates. a) Santa Isabel in Puerto Rico; b) Finca Atabey in Santa Isabel; and c) Finca Atabey, a multi-crop agricultural farm in Santa Isabel, Puerto Rico. From *Google Earth*.



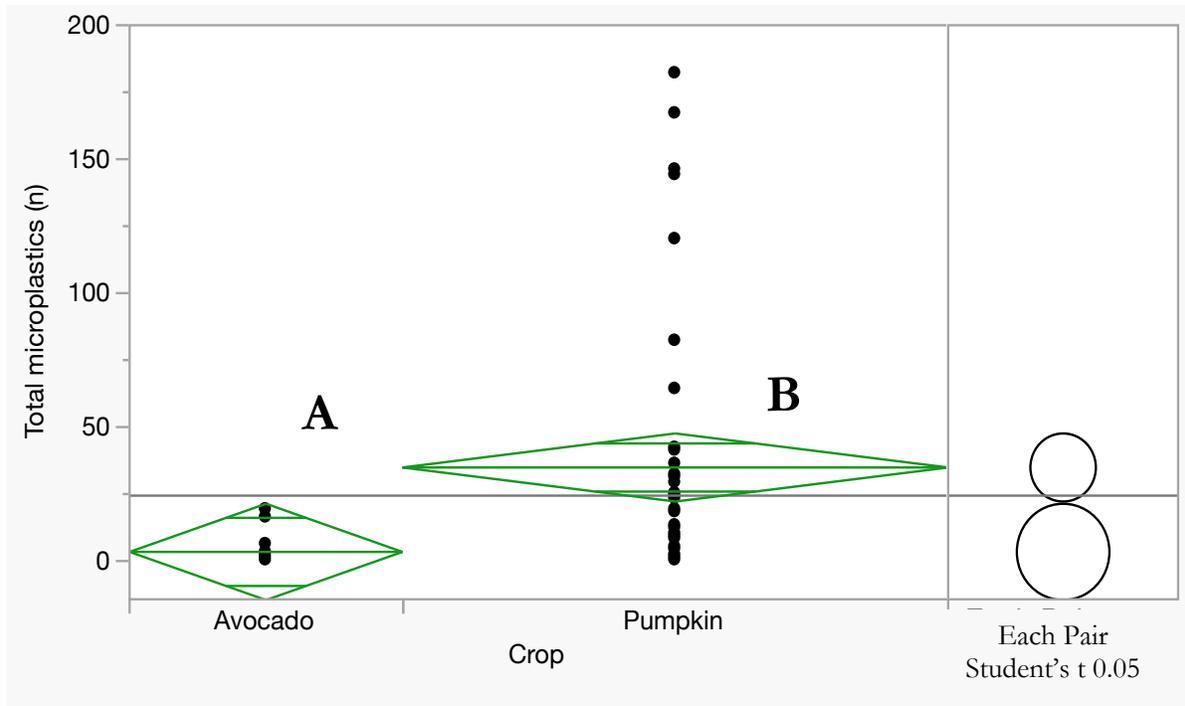
**Figure 2.** Types of crop sampled. a) Avocado field; b) Pumpkin field, biodegradable plastic. c) Pumpkin field, fragmented biodegradable plastic.



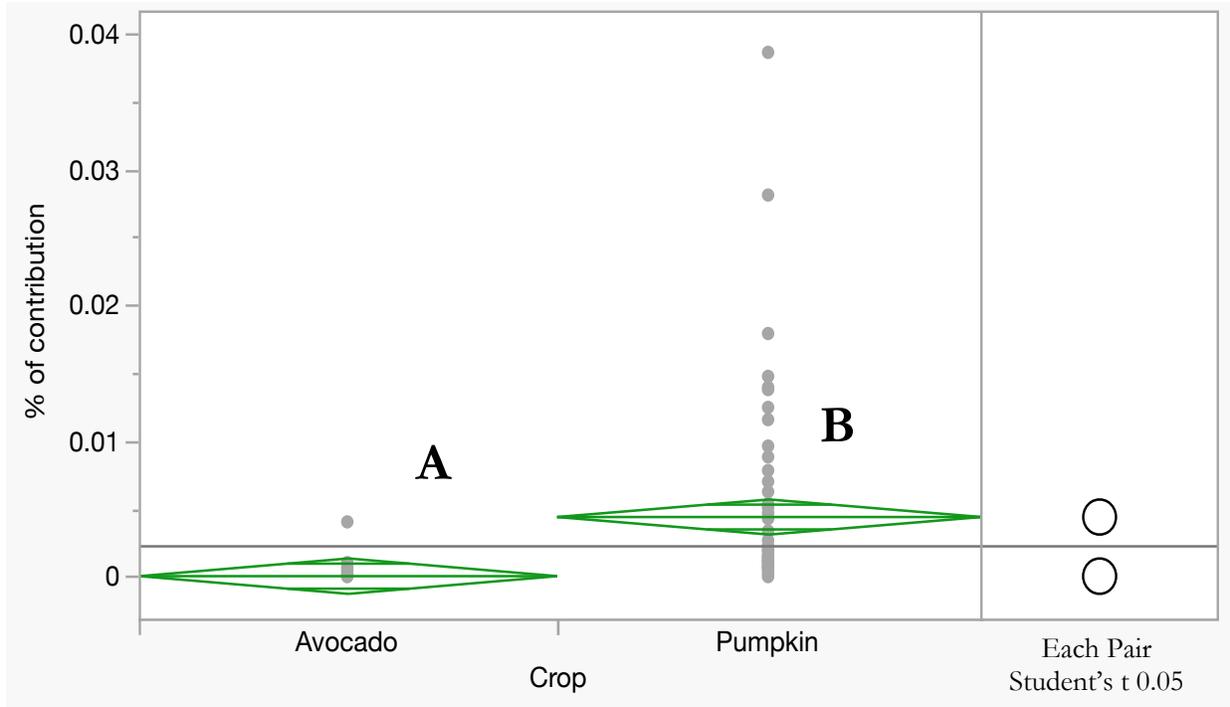
**Figure 3.** Types of plastic debris found. a) Non-biodegradable microplastics >4.75 mm; b) Non-biodegradable microplastics 2.00-4.75 mm; c) Non-biodegradable hose plastic debris (114.04 mm); d) Biodegradable microplastics 2.00– 4.75 mm; e) Non-biodegradable microplastics 1.00 – 2.00 mm.



**Figure 4.** Histogram for the total quantity of microplastics per crop type: avocado and pumpkin.

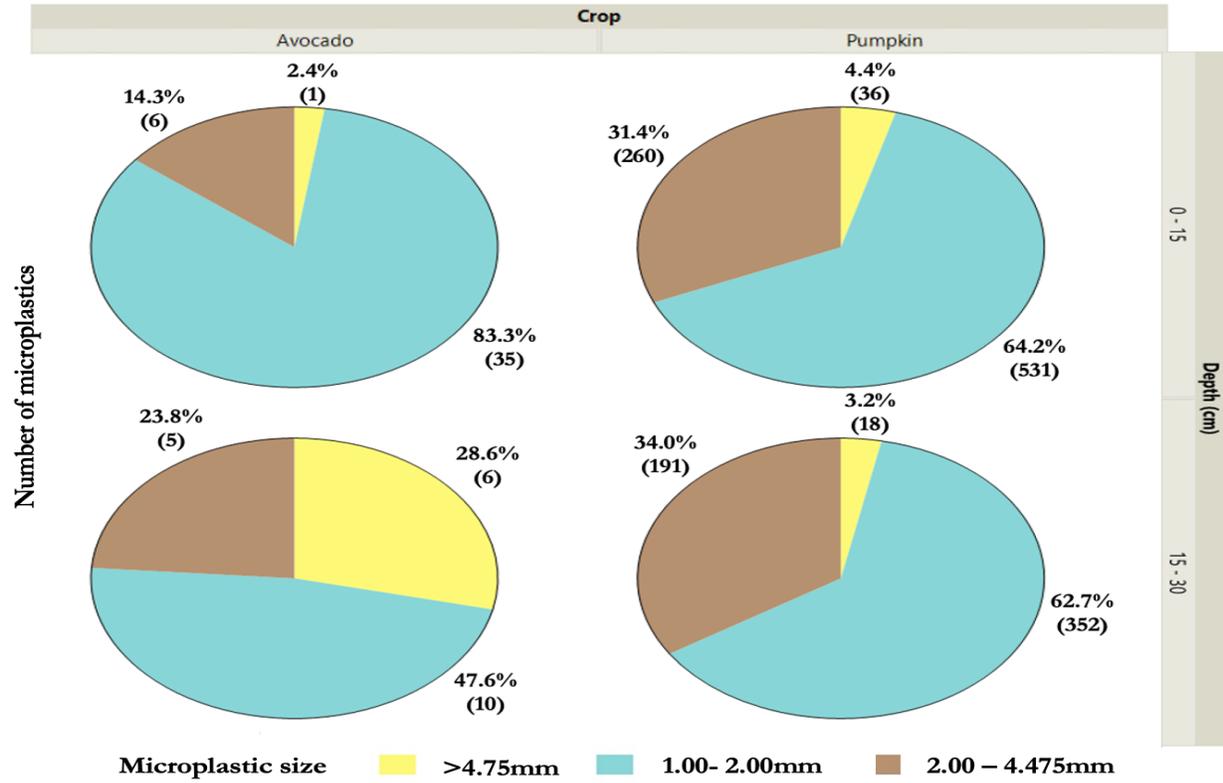


**Figure 5.** Total microplastics per crop type: avocado and pumpkin. Levels not connected by the same letter are significantly different.

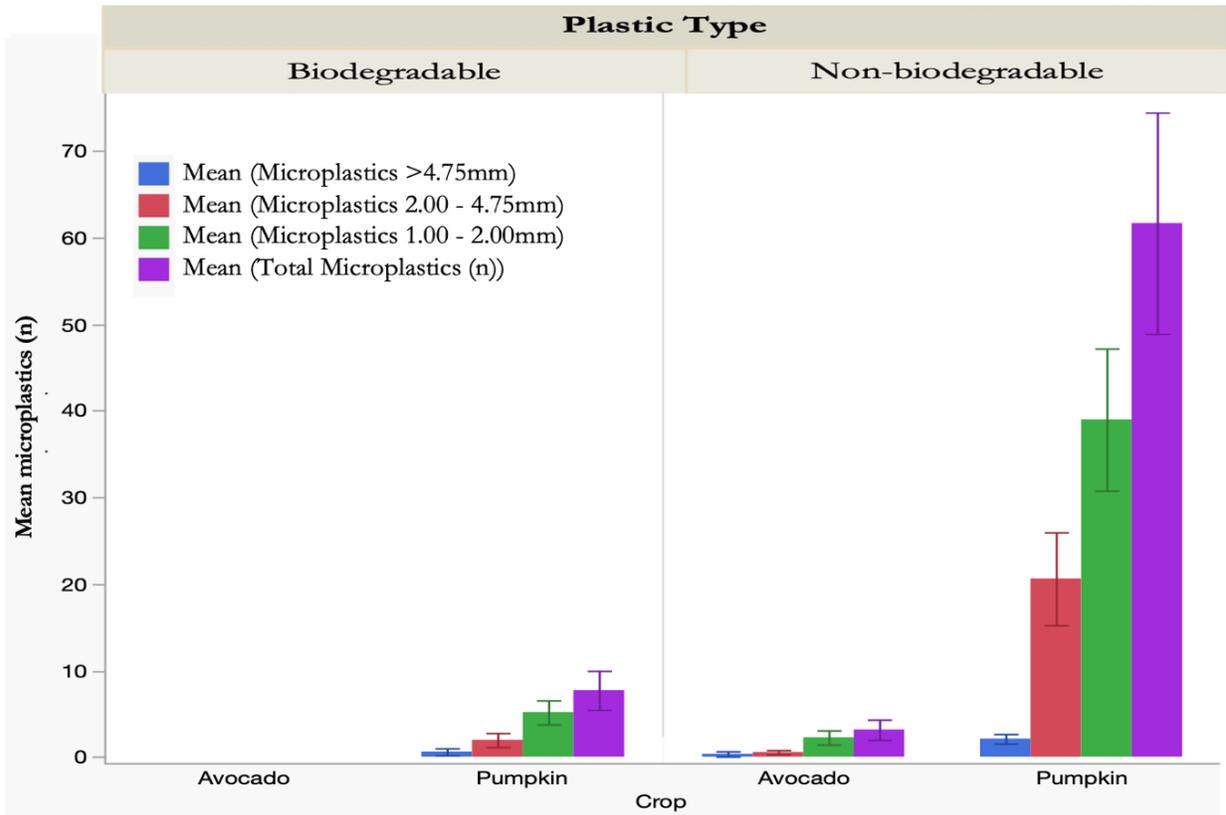


**Figure 6.** Percentage of contribution of microplastics per crop type: avocado and pumpkin. Levels not connected by the same letter are significantly different.

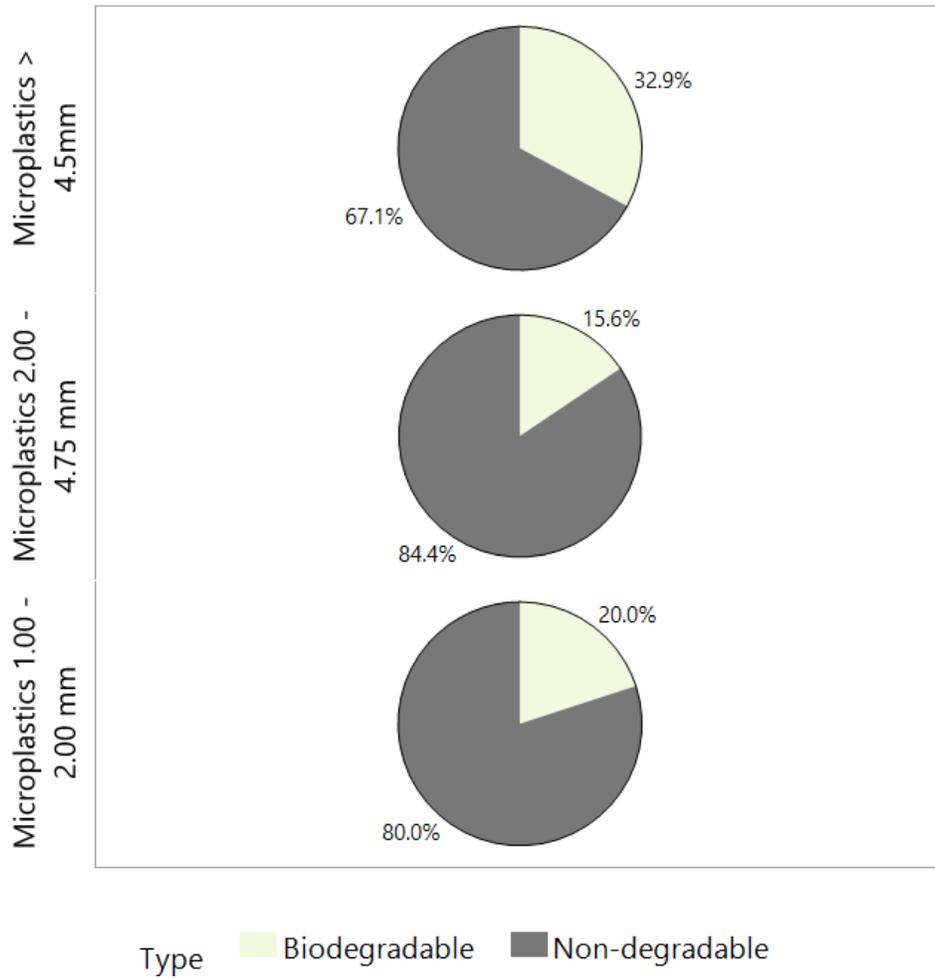




**Figure 8.** Number of microplastic per size, crop, and depth.



**Figure 9.** Mean microplastic per crop type: avocado and pumpkin and by plastic type: biodegradable and non-biodegradable.



**Figure 10.** Percentage of plastic type: biodegradable and non-biodegradable, per size studied (>4.75 mm, 2.00-4.75 mm, and 1.00-2.00 mm) in the pumpkin field.