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Upcycling the Banana Industry in Ecuador: A Methodology to Estimate Biowaste and Catalogue of Bioproducts

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***Abstract*— Ecuador is the leading exporter of bananas globally. This industry generates a large amount of organic waste since the plant is cut down for every crop, but only the fruit bunch is used. These residues can be converted into sustainable environmental products that could replace polluting materials. This investigation presents a GIS-based methodology used to estimate the biomass of the residues of banana agriculture in Ecuador and to determine how much organic waste could be used as raw materials to manufacture new biodegradable products. We estimated that more than forty million metric tons of waste are produced every nine months. Our methodology can be a low-cost quantitative complement to the survey-based estimations conducted by the Ecuadorian government to evaluate banana production. Additionally, our work presents five products that could be manufactured with organic waste, like disposable plates, bioplastics for food utensils, cardboard covers, fibers for hydraulic cement, and wallpaper. Finally, we offer a product catalog developed as a technical guide for future bio-enterprises to elaborate biodegradable products inspired by a circular economy scheme. In light of the estimated amount of banana waste generated in the country, we consider that Ecuador has the potential to develop an industry based on this raw material to generate products such as those proposed in our review, shifting the banana industry to a more sustainable, profitable process, and generating new incomes and sources of employment.**

***Keywords*— Circular economy; agricultural residues; biomass; banana; biodegradable products.**

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I. INTRODUCTION

The global production system is based on the linear economy scheme: companies extract raw materials that are refined, assembled, and consumed as products that become garbage at the end of their useful life. Under this scheme, the products in all their stages continuously need new natural resources in the form of raw materials and consume energy that generates greenhouse gases [1]. Nowadays, 70% of the world's garbage is plastic, and 50% comes from single-use disposable products such as bottles and containers [2]. This plastic is produced with oil, a non-renewable resource that is increasingly scarce, more expensive to extract, and of poorer quality [3]. These materials are toxic and not biodegradable, so they remain in the world's ecosystems for months to centuries. Added to this mass production of plastic waste, paper and cardboard are also extensively used for product packaging. Although they are biodegradable and are not as toxic as plastic materials, the production cycle of paper and cardboard also has high environmental impacts, and they are among the industries that most pollute water and air [4].

Nowadays, the contamination of ecosystems is the fourth cause of biodiversity loss, affects human health, and causes economic loss worldwide. We produce 2% and 5% of plastic waste in the sea and lakes [5]. In the water, these materials slowly decompose and break down into small fragments of less than 5 mm in diameter, known as microplastics, already found on every corner of the planet [6].

There are new sustainable production schemes based on three main principles to face these problems: implementing circular economy production systems, using raw materials from agricultural waste, and creating biodegradable and innocuous products. A Circular economy is a production and consumption model in which key actions such as innovating, sharing, renting, reusing, repairing, renewing, and recycling existing materials and products are applied as often as possible to create added value. In other words, the production chain, in all its stages, tries to obtain added value and, due to the overflow effect, lengthens the useful life of the products [7].

Using agricultural residues could maximize the productivity of cultivated land without compromising food security. This could be possible with some crops that generate substantial waste because only food is used, leaving aside an enormous amount of vegetal biomass. This waste biomass could be used as raw materials in a circular economy scheme to generate products made from biodegradable fibers [8].

This kind of production alternative is a reality in Ecuador. Some companies are already manufacturing products with biodegradable raw materials, from sophisticated cassava starch covers to sugar cane bagasse paper. However, the country has immense potential to manufacture other sustainable products following these circular economy schemes, making the most out of other crop residues [9].

Ecuador is the first banana-exporting country in the world [10]. The magnitude of this activity is such that 0,92% of the national surface, 261.445,90 hectares, are used for its cultivation[11]. This represents a great opportunity to manufacture products with biodegradable fibers from banana agriculture's waste biomass.

The most cultivated banana variety in the country is *Musa paradisiaca*. However, other varieties of this species are widely cultivated in the national territory. Depending on how they are consumed, they are named differently: plantain is when the fruit is cooked and harvested unripe, while banana is consumed raw, as a fruit, and it is harvested ripe [12]. In this manuscript, the term banana is used to refer to all the varieties and harvest types. Although there are some differences depending on the variety and the moment it is harvested, as a rule, 80% of the plant's biomass is wasted. This is because when the fruit is harvested, the entire plant is cut down, but only the fruit bunch is used, discarding the vegetative part of the plant, the stem, the rachis, and leaves, which may be used as new raw materials [13], [14].

Considering the aforementioned context, we wanted to know if there is a potential in Ecuador to create an industry based on the manufacture of biodegradable products from the residues of banana agriculture, replacing plastic-based and toxic disposable products and creating new job opportunities. We hypothesize that this untapped potential comes from the lack of knowledge in biotechnology and biocommerce.

Hence, two research questions arose:

- How much biomass from the residues of the banana activity in Ecuador is available to generate products that can potentially replace other non-renewable materials?
- What products could be generated with this residual biomass that could offer a sustainable alternative to polluting materials such as plastics?

To answer those questions, the objectives of our research were: a) to develop a low-cost methodological proposal to estimate the biomass of residues of the banana industry in Ecuador and assess its feasibility as a source of raw biodegradable materials; b) to offer a catalog of potential uses of banana plant residues to promote a change on the productive system in the country towards a circular economy and foster local bio-entrepreneurship.

II. Materials and Method

To know the surplus biomass of all the banana activity in Ecuador, three variables were considered:

- Number of hectares of banana cultivation in Ecuador and its distribution in the territory.
- The mean number of banana plants per hectare in Ecuador
- Average weight in kilograms of the vegetative part of the banana plant after harvesting the fruit bunch.

Raw data were obtained from the Ministry of Livestock and Agriculture (MAG) [15] in 2017 to know the extension of hectares of banana cultivation in the country and its distribution. With this “Geo tiff” format layers, a map of the agricultural land cover of these crops was set using ArcGIS 10 software.

Two different GIS-based methods were used to count the number of plants per crop area, also using ArcGIS 10. The first method used high-resolution images of banana crops taken by drones. These images were digitized into polygons where every plant was marked with a point within the boundaries of the polygons, resulting in a dot matrix for the selected area (see Figure 1, images a and b).

In the second method, we sampled a high-resolution satellite image of banana fields of 1.610 hectares coming from La Mana, Province of Cotopaxi. Ten parcels of one hectare were randomly selected in this territory using the “Net fish” tool. In each one of these square parcels every plant was counted and marked manually with a point, forming dot matrixes (see Figure 1, image c).

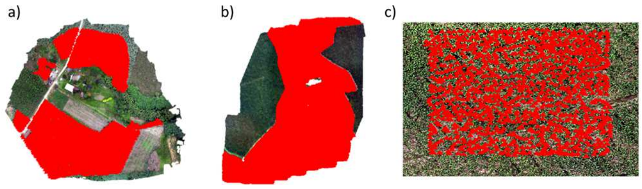

Fig. 1 High-definition orthophotos taken by drones used to count plants by surface. The three images belong to the Ecuadorian coastal region (see Figure 2): a) surface of 5,86 hectares of banana in the Province of Los Rios, Quinsaloma Parish; b) area of 45,66 hectares of banana in the Province of Los Ríos, Quevedo Parish; c) High-resolution satellite photograph and a randomly delimited one-hectare square plot. Plants inside the plot are marked with a red dot. Province of Cotopaxi, La Mana. Scale 1:5000

The results of both GIS methods were compared through a meta-analysis with the data obtained from three previous research: the first source presented results from surveys on farmers in the banana sector by the National Institute of Surveys and Censuses of Ecuador INEC [15]; the second source is surveys by the Ministry of Agriculture and Livestock that asked about the number of plants per hectare in the banana industry in the country [11]; the third reference document is a report on plant phenology of banana crops with a national reach [16]. The meta-analysis and data comparison were done through box-and-whisker graphs using the R studio Program.

For variable 3, to estimate the average weight in kilograms of the vegetative part of the plant after harvest, an in-situ sampling was conducted in three localities on the Ecuadorian coast. Each one of those localities was selected as a reference for the three scales of banana cultivation in the country: small (1 to 5 hectares), medium (5 to 30 hectares), and large (above 30 hectares) cultures. The localities were: Troncal de la Costa route, kilometer 10 (small); Villegas, route between Monterrey and Boca de Chilla (medium); El Pimiento, Spondylus route (large). Ten plants were weighed, five for the banana variety and five for plantain. The plants were cut into pieces with a machete to be weighed by a hanging scale, and the weight of each part was added to obtain the total weight of the vegetative part of the plant. With the information collected in situ, a meta-analysis was conducted comparing the field data with bibliographic sources on plant physiology to reduce the error [11]. Once the three variables were obtained, the data were multiplied in the following way to estimate the waste biomass potentially available as raw materials in the country, see, eq (1).

Biomass = {(Total hectares of banana in Ecuador) * (Mean banana plants per hectare) * (Mean weight of the vegetative part of the plant after harvest)}. (1)

III. Results and Discussion

A. Biomass estimation

As the Ministry of Livestock and Agriculture reported, there were 261.445,90 hectares of banana plantations in Ecuador in 2017: 181.581,18 hectares are banana crops, and 79.864,72 belong to plantain crops [11]. Most of them were distributed along the occidental foothills of the Andes, on the coastal territories of the country: Santo Domingo de los Tsachilas, Manabí, Los Ríos, Guayas, and El Oro Provinces (Figure 2). The map shows the categories above related to the consumption type and harvesting moment: banana, ripe fruit consumed raw, or plantain, unripe fruit for cooking.

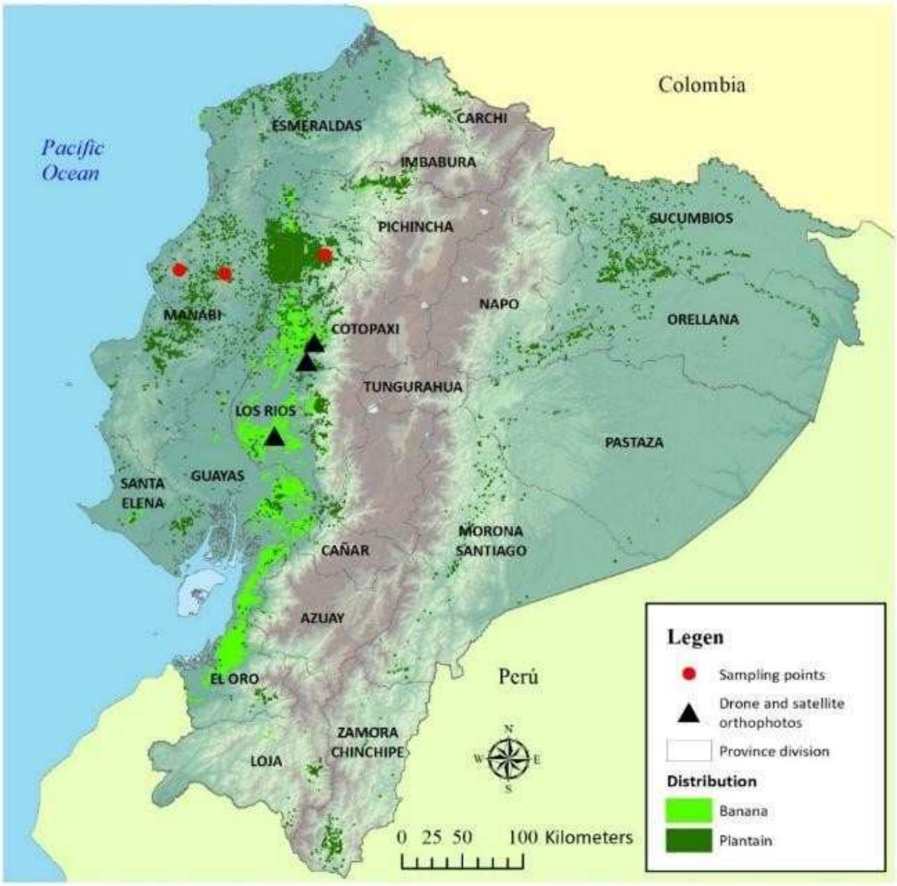

Fig. 2 Map of banana agriculture distribution in the country. Dark green for plantain and light green for banana crops. Banana weight sampling localities are marked with red dots. Black triangles indicate reference sites where drone and satellite orthophotos were taken to estimate the number of plants per hectare. Data from the Ministry of Livestock in the year 2017 [11].

The northern territories mainly produce plantains, while banana cultures dominate the central and southern cultures. Regarding the number of plants per hectare, Figure 3, plot a, shows the comparison between the data obtained using the two proposed GIS methods: polygons in drone images found a mean of 1044 plant/ha (box 1), while random plots on a satellite image found a mean of 1320 plants/ha (box 2). The data found in the literature gives a mean of 1740 plants/ha (box 3). Considering the results of the three data sets, the average number of plants per hectare was 1368 plants per hectare (box 4).

Concerning the weight of the vegetative part of the plants, Figure 3, plot b, shows the comparison between the mean weight obtained from in-situ sampling in kg, which resulted on a mean of 133 kg (box 1), the mean weight reported by literature in kg, being a mean of 151 kg (box 2), and the average of both data sets, 142.41 kg (box 3).

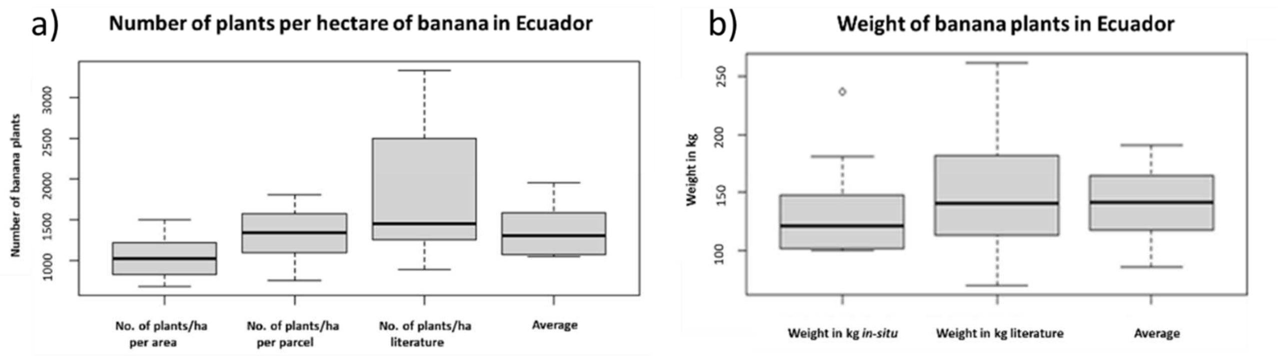

Fig. 3 Map of banana agriculture distribution in the country. Dark green for plantain and light green for banana crops. Banana weight sampling localities are marked with red dots. Black triangles indicate reference sites where drone and satellite orthophotos were taken to estimate the number of plants per hectare. Data from the Ministry of Livestock in the year 2017 [11].

Finally, considering the banana plantation surface, the estimated number of plants per hectare, and the estimated average weight of the plant, the total banana biomass was calculated (Table 1). According to the literature, the fruit bunch represents 20% of the plant's weight. Therefore, we subtracted that from the total weight and obtained that 40.601.335,16 tons of organic waste are produced in Ecuador for every banana harvesting cycle every nine months [13].

TABLE I
DATA SET TOKEN FOR THE CALCULATION OF THE BIOMASS OF THE PLANTS OD THE BANANA ACTIVITY IN ECUADOR

Banana plantation surface	Means number of plants per hectare	Average plant weight	Total biomass	Biomass without fruit bunch
261.445,90 ha	1368	141,9 kg	50.751.668,95 t	40.601.335.16 t

B. *Product Catalog*

To explore the potential products that could be generated with this residual biomass, we prepared a catalog to be used as a technical informative guide for scientific dissemination. The five selected products were disposable plates, bags, bioplastic utensils, hydraulic cement, and wallpaper (Figure 4). The guide offers information for bio-entrepreneurs about what could be manufactured and how to produce it using banana waste. Since the largest number of banana production comes from small and medium-sized enterprises [16], the production scheme was based on plantations of no more than thirty hectares and with community management. To foster and facilitate new entrepreneurship, we prepared infographics with technical guides (Figure 5) for each selected product, including practical information about the elaboration process, the required equipment, and the minimum budget for producing them (Table 2). Due to space limitations, only one of them is presented in the manuscript. The catalog with the five products and the infographic with the production process for each one of the five presented products can be found and downloaded at the following link: https://figshare.com/projects/Upcycling_the_banana_industry_in_Ecuador/148243.

Product	Description
	**Disposable plates** made from banana leaves, based on the design of the German company Leaf Republic. Degrades in 28 days after use, works as a land fertilizer and is innocuous for the environment. Each banana leaf produces up to two 25 cm diameter disposable plates [14].
	**Cardboard paper bags** made from the stem of the banana plant. Degrades in three months, while a common papercardboard takes one year to degrade. Each stem produces up to eight 20 x 15 cm cardboard bags [17].
	**Biodegradable bioplastic utensils** made from the heart of the banana stem. Plates, cutlery, and glasses: resistant, impermeable and hardness comparable to ordinary plastics. They biodegrade in 5 months and work as fertilizer, providingnutrients such as carbon and potassium to the soil [18].
	Splinter of the banana rachis to make **hydraulic cement** used to build roads. Replaces plastic or carbon fibers used in the concrete. Adding 0,3 to 0,7% of banana rachis chips, the cement is 20% more resistant than conventional cement. Increases the impermeability, contraction, and expansion of theconcrete. Great alternative for road construction in tropical climates [19].
	**Wallpaper** made from the heart of the stem of the banana plant. It does not need glue to stick the fibers. Cured with linseed oil, can have a useful life of 10 to 15 years in dry climates. After disposal, it biodegrades in 9 months, becomes fertilizer, and does not have any toxic substances as conventional wallpapers [20].

Fig. 4 Selection of biodegradable products in the catalog that could be elaborated with banana waste biomass, based on product designs of existing companies and data from previous research [14], [17]–[20]

C. Discussions

Based on our results, we consider that Ecuador has the potential to develop an industry based on banana waste as a raw material, able to produce biodegradable products such as those proposed in our review. According to our calculations, more than forty million tons of biomass are available in the country every nine months, the time it takes to complete a harvesting cycle to conclude [21], representing around 194 metric tons of biomass per hectare on average. Considering that most of the crops are located in the coastal area, we recommend that this new industry be established in the country's western area, close to the banana agriculture lands.

Our methodology can be a feasible alternative to cheaply and quickly estimate the biomass of banana residues available in the country. Nowadays, the official data to evaluate banana production in Ecuador come from surveys to producers [11], [15], [16], which are costly and can be subjective. Therefore, we consider that our GIS-based, empirical, and low-cost methodology could be used to obtain solid estimations of banana production and complement or replace the surveys.

Moreover, our spatial model was generated with available public data from 2017, and considering that the banana sector in 2021 reported a significant increase in hectares of cultivation (from 180.000 in 2017 to 190.000 hectares in 2021) [11], our results are probably underestimating the currently available biomass.

TABLE II
REFERENTIAL COSTS IN EQUIPMENT AND MATERIALS IN ECUADOR TO START AN ARTISAN FACTORY OF BIO-DEGRADABLE PLATES OF BANANA LEAVES

Equipment and materials	Price per unit
PB40-900 m roll of biodegradable cotton thread	49.90 $
Paper scissors or stylus	2 $
Industrial overlock sewing machine	30 $
20-ton hydraulic heat press	1200 $
Electro-welded steel plate molds: 23 cm Ø; 5 cm depth	50 $
Banana leaves	Unknown value per unit
One gallon can of food sanitizer	25 $
Rental of a 60 m2	1800 $ for six months

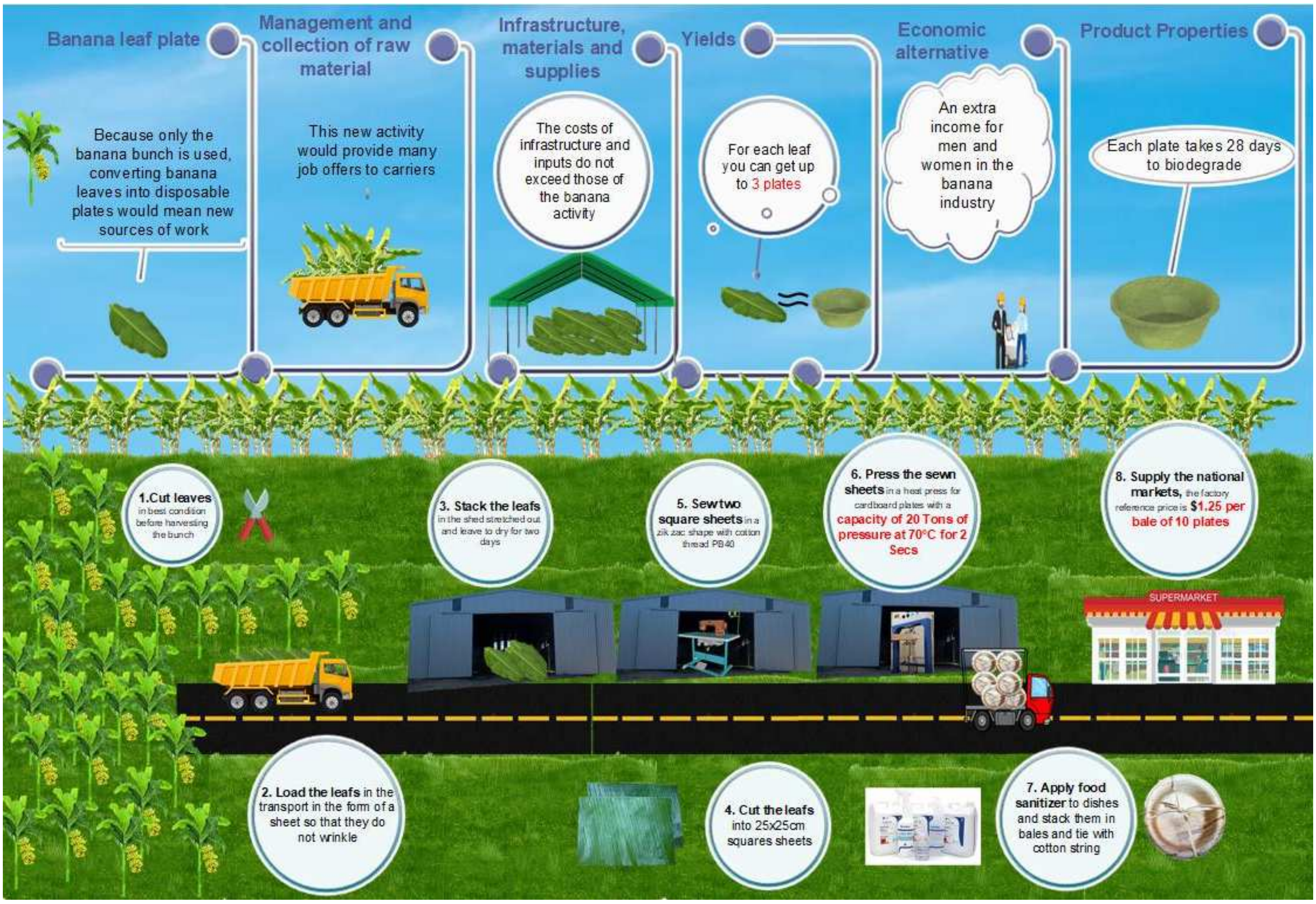

Fig. 5 Infographic for the process of elaboration of disposable plates made from banana leaves. The high-resolution image can be found and downloaded on the following link: https://figshare.com/articles/figure/Infograpihc_Banana_leaf_plates/20819911

However, when considering the number of plants per area, the values reported by the literature were generally higher than those found in our spatial model [11], [15], [22]. This is probably due to the limitations of satellite and drone imagery. In the in-situ sampling, we found that it is common to find that banana plants have up to five shoots coming out from the same plant, and the largest plant covers the smaller ones out of aerial view, although the smaller plants managed to produce fruit clusters in the same harvest separated briefly in time. The same trend was observed for the average weight of banana plants, in which the literature values were again higher than those found in situ [13]. This is probably due to the small sample size with only ten plants. Although we did not consider the differences between the waste biomass produced by bananas and plantains, we found that bananas had slightly higher weights than when the fruit was harvested un-ripe as plantains. This difference may be significant at a national scale and should be considered for further research.

The limitations to determining the current area under banana crop, the undercounting of the number of banana plants per hectare, and the underestimation of the average weight of the plants, may have influenced the calculated biomass value of the banana activity in Ecuador. Although our methodology needs to be fine-tuned by taking more reference data in the field, it serves as a reference approach to estimate the biomass of banana residues available and has the potential to become a useful tool.

Nevertheless, it is necessary to consider that extracting the residues from banana agriculture would result in removing a large amount of organic matter that is usually used as fertilizer, leaving it in the field to decompose. Nonetheless, an excess of organic matter in the land is one of the causes of the *Fusarium* spp. Fungus proliferation [23]. This fungus has caused massive loss of banana plantations around the world and even caused the extinction of some banana varieties. Many studies indicate that reducing the organic matter in soil decomposition could stop this pest's proliferation in banana crops [24]. Therefore, extracting some waste biomass could reduce the risk of fusarium plagues and offer raw materials for a new sustainable industry without affecting the productivity of the crops. Nonetheless, more research is necessary to determine how much biomass could be removed from banana crops without excessively removing nutrients from the soil and whether removing excess biomass would curb the largest pest of the crop that strongly threatens this activity. These knowledge gaps must be answered to determine how feasible it is to manufacture products from banana residues massively and upcycle the banana industry in the country to circular economy schemes.

IV. Conclusion

Our study highlights the urgent need to address the environmental impact of the linear economy, characterized by resource extraction, production, consumption, and waste disposal. This system, driven by single-use products and non-renewable resources like oil, has led to a global plastic waste crisis, contaminating ecosystems and generating long-lasting harm. In response, sustainable production approaches are gaining traction, centered on circular economy models, using agricultural waste as raw materials, and creating biodegradable products. As a major banana exporter, Ecuador offers a unique opportunity to adopt such models. Banana plantations produce substantial organic waste, often overlooked. Our research introduces a cost-effective methodology to estimate the biomass of banana plant residues in Ecuador, providing a basis for future sustainable industry development. This includes a catalog of potential biodegradable products and technical guides for bio-entrepreneurs. Ecuador's banana industry can be pivotal in reducing its environmental footprint, promoting circular economy principles, and fostering local bio-entrepreneurship. However, ongoing research is vital to balance waste biomass removal and soil health, address bio-entrepreneurship challenges, and scale up sustainable production. In summary, Ecuador's banana industry has the potential to revolutionize waste utilization, reduce environmental harm, and contribute to a more sustainable and economically viable future.

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