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Article

Sustainable Development and Yield, Morphological, Biochemical and Ecotoxicological Characterization of Banana Peel Biofertilizer

Juliana Dantas da Costa[1], Melissa Castro da Silva[2], Ana Beatrice Melo Aguiar[3], Matheus Sousa Silveira[4], Tamiris Bezerra Costa[5], Igor Iuco Castro-Silva[6]

[1] Master in Dentistry. Member of Biomaterials Laboratory, Postgraduate Program in Dentistry, Federal University of Ceara (UFC), Fortaleza, CE, Brazil. ORCID: 0000-0002-3321-6436. E-mail: julianadantas@alu.ufc.br

[2] Undergraduate medical student. Member of Biomaterials Laboratory, Academic Initiation Scholarship Program, Federal University of Ceara (UFC), Sobral, CE, Brazil. ORCID: 0009-0007-2069-8505. E-mail: melissacastro13@alu.ufc.br

[3] Undergraduate dentistry student. Member of Biomaterials Laboratory, Institutional Scholarship Program for Initiation in Technological Development and Innovation, Federal University of Ceara (UFC), Sobral, CE, Brazil. ORCID: 0009-0008-6043-5862. E-mail: beatrice.melo@alu.ufc.br

[4] Undergraduate dentistry student. Member of Biomaterials Laboratory, Institutional Scholarship Program for Initiation in Technological Development and Innovation, Federal University of Ceara (UFC), Sobral, CE, Brazil. ORCID: 0009-0002-1742-1445

[5] Undergraduate dentistry student. Member of Biomaterials Laboratory, Institutional Scholarship Program for Scientific Initiation, Federal University of Ceara (UFC), Sobral, CE, Brazil. ORCID: 0009-0002-4189-2474. E-mail: tamirisbc@alu.ufc.br

[6] Doctor in Dentistry. Environmental Education Teacher and Head of Biomaterials Laboratory, Postgraduate Program in Biotechnology, Federal University of Ceara (UFC), Sobral, CE, Brazil. ORCID: 0000-0003-4815-6357. E-mail: igor.iuco@sobral.ufc.br

ABSTRACT

Organic fertilizers derived from solid food waste, such as banana peels, represent a promising circular model for mitigating waste and enhancing biotechnological innovation. This study aimed at the sustainable development of a biofertilizer from discarded *Musa sapientum* peels. Fresh samples were obtained through selective collection in a university restaurant in the interior of Ceará and carried out quantitative indicators. Pilot study with four collections tested different time-temperature processing for dehydration and flour prototyping. Based on the best morphological aspects of pilots 3 and 4, the operational protocol was chosen for the second phase, with eleven collections subjected to a continuous cycle of automated dehydration at 70°C for 12h, grinding and sieving. The yields of each cycle were analyzed, considering the weight of wet and dry matter. Biochemical analysis detected the presence of the macronutrient nitrogen, phosphorus and potassium and pH in aqueous solutions in quintuplicates. Ecotoxicological analysis was conducted in an *Artemia salina* model for 24h of direct contact with three batches of fertilizer in different concentrations and in quadruplicate. Banana peel was an economical option, and the chosen protocol provided a homogeneous product with medium grain size. Despite the substantial reduction in sample volume, there was a predictable yield of an average of 10.3%, suggesting potential for scalability. The concentration of macronutrients remained within the expected range for a fertilizer for acidic soils, with low nitrogen and high phosphorus and potassium content, which explains the alkalizing effect on pH. There was no toxicity at the low concentrations tested up to 10,000μg/mL, maintaining a lethal concentration below 50%. Banana peel flour showed favorable structural properties for use as biofertilizer. Future studies will be able to elucidate its effectiveness in green areas on the campus and the impact on environmental compliance of the endogenous demand for waste at the university.

Keywords: Musa; fertilizers; sustainable development; biochemistry; ecotoxicology.

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RESUMO
Fertilizantes orgânicos derivados de resíduos sólidos alimentares, como a casca de banana, representam um modelo circular promissor para mitigar o lixo e potencializar a inovação biotecnológica. Este estudo objetivou o desenvolvimento sustentável de um biofertilizante a partir de cascas descartadas de *Musa sapientum*. Amostras frescas foram obtidas através de coleta seletiva em um restaurante universitário do interior do Ceará e realizados indicadores quantitativos. Estudo piloto com quatro coletas testou diferentes processamentos tempo-temperatura para desidratação e prototipagem de farinhas. A partir dos melhores aspectos morfológicos dos pilotos 3 e 4, foi escolhido o protocolo operacional para a segunda fase, com onze coletas submetidas ao ciclo contínuo de desidratação automatizada a 70ºC durante 12h, trituração e peneiragem. Foram analisados os rendimentos de cada ciclo, considerando peso da matéria úmida e seca. Análise bioquímica detectou presença de macronutriente nitrogênio, fósforo e potássio e do pH em soluções aquosas em quintuplicata. Análise ecotoxicológica foi conduzida em modelo de *Artemia salina* por 24h de contato direto com três lotes do fertilizante em diferentes concentrações e em quadruplicata. A casca de banana foi uma opção econômica e o protocolo escolhido gerou um produto homogêneo e de granulometria média. Apesar da redução substancial no volume das amostras, houve rendimento previsível na média de 10,3% sugerindo potencial de escalabilidade. A concentração dos macronutrientes manteve-se dentro do esperado para um fertilizante de solos ácidos, com baixo teor de nitrogênio e alto de fósforo e potássio, o que explica o efeito alcalinizante no pH. Não houve toxicidade nas baixas concentrações testadas até 10.000μg/mL, mantendo concentração letal inferior a 50%. A farinha de cascas de bananas apresentou propriedades estruturais favoráveis para uso como biofertilizante. Futuros estudos poderão elucidar sua eficácia em áreas verdes do campus e o impacto para conformidade ambiental da demanda endógena de resíduos na universidade.
Palavras-chave: Musa; fertilizantes; desenvolvimento sustentável; bioquímica; ecotoxicologia.

Introduction

Sustainable development, a concept that emerged in the Brundtland Report of the World Commission on Environment and Development created by the United Nations (UN) in 1987, interconnects the social, economic, ecological, spatial and cultural dimensions, with transversal emphasis on international policies the reuse of solid waste in recent decades (Fernandez 2011). The Sustainable Development Goals of the 2030 Agenda commit to preserving the environment and soil, through targets for sustainable cities and communities, sustainable consumption and production and life on land, equivalent to around a quarter of the UN's global investments (Organização das Nações Unidas 2015). The climate urgency scenario requires a change in organizational culture in institutions, in alignment with strategies related to the environment, social and governance (ESG), where combating the large production of waste and alternatives to the scarcity of natural resources are highlighted (Bathmanathan et al. 2023). It has been estimated that 931 million tons of food are wasted annually in the world, 26% of which originates from food services (Ferreira et al. 2023).

Organic waste in Brazil corresponded to 45% of total urban solid waste and reached 230 million tons per year, and the National Solid Waste Plan sets a target by 2040 of 13.5% of this total mass being destined for mechanical-biological treatment, which consists of processing through composting or anaerobic digestion to generate new inputs (Brasil 2022). In parallel, the National Fertilizer Plan seeks sustainable alternatives to mitigate non-renewable extractivism, given the increase in fertilizer consumption, the decrease in mineral deposits in the soil, dependence on the international market for the supply of potassium, phosphorus and nitrogen and the need for food security to nine billion people by 2050 (Nascimento et al. 2025). Organic fertilizers can achieve this synergy of intentions, representing a path of degradation and stabilization of waste in controlled and safe conditions for human health, recycling nutrients to enrich the soil (Brasil 2022). However, scientific production and technological innovation of biofertilizers in Brazil is still incipient and needs to be stimulated (Silva et al. 2021b).

The production of more stable and mineral-rich organic fertilizer can be done with various environmental methodologies and generate products in different states, as is the case with banana peel biofertilizer in the form of substrate, powder, biochar or liquid (Mishra et al. 2023). The use of less complex and faster technologies, such as dehydration or drying, may be more advantageous (Neris et al. 2008; Pessoa 2009). In fact, composting is more widespread because it is more economical and targets organic products that are easier to segregate at the source of large generators: waste from street markets, municipal markets, maintenance of green areas, restaurants and community initiatives (Brasil 2022; Martin-Rios et al. 2022). Food and Nutrition Units (FNU) were present in 89% of federal universities in Brazil according to Deliberador et al. (2021) and generated a large daily demand for organic matter disposal, ranging from just 20 kg according to Silva et al. (2021a) up to 830 kg observed by Silva et al. (2021c). The partial value of organic waste including counter leftovers and rest-ingestion over the total discarded waste, containing dry paper or plastic waste, could vary from 12% (Zotesso et al. 2016) to 98% (Silva et al. 2021c). Such heterogeneity can be justified by the daily service flows of the FNU, ranging from just 440 meals as observed by Forner and Conto (2020) to up to 10,000 meals recorded by Rodrigues et al. (2019). Furthermore, recent studies on FNU showed a geographic concentration, suggesting that cultural or demographic factors in large urban centers imply more evidence in the South Region (Zotesso et al. 2016; Rodrigues et al. 2019; Silva & Souza 2019; Forner & Conto 2020) than the Southeast (Domingues et al. 2016; Deliberador et al. 2021; Silva et al. 2021c), Northeast (Carneiro 2013; Menezes & Anjos 2017; Ferreira et al. 2023), Central-West (Candida et al. 2021) and North (Silva et al. 2021a).

When using food by-products for the circular economy, bananas pay special attention to tropical countries where they are mostly cultivated (Acevedo et al. 2021). There is great versatility of biotechnological applications for bananas, such as fermentative processes, bioplastics, organic fertilizers, biofuels, wastewater treatment and nanomaterials for human health (Redondo-Gómez et al. 2020; Acevedo et al. 2021; Tadesse et al. 2023). Banana peel (Musa spp.) has attracted increasing interest, as it is considered an inevitable waste, just like bones (Deliberador et al. 2021). The amount of peel reaches 40% of the total weight of the fresh fruit (Acevedo et al. 2021). Banana peel for fertilizer production is attractive due to its low cost, but the diversity of processing protocols and mixtures with other substrates makes reproducibility and interpretation of results difficult (Ferreira et al. 2015; San & Aung 2021; Saniya et al. 2023). A review of the use of banana peels as biofertilizers by Acevedo et al. (2021) summarized that the composting method for 60 days is the most chosen, generating from 2.13 to 17.21% of nitrogen, 0.57% to 10.24% of phosphorus and 7.68% to 48.32% potassium, as well as calcium, magnesium, iron, copper and zinc, with a pH of 7.9 to 8.4. Such elements are fundamental for plant growth, maintaining the biomolecular integrity of proteins, nucleic acids, energetic function and plant electrolyte balance and regulating the typical acidity of soils through their alkalinizing effect (Nascimento et al. 2025). Even with natural derivation, organic fertilizers need to be simulated testing in biological systems to determine their impact on the ecosystem and safety of use (Meyer et al. 1982).

To promote food waste management in a university FNU and stimulate innovation with a new biotechnological product, this study aimed at the sustainable development of a banana peel-based biofertilizer and its yield, morphological, biochemical and ecotoxicological characterization.

Material and Methods

Study design

The methodological typology of this scientific study followed an experimental laboratory modality, with an analytical objective and a quantitative approach.

Ethical aspects

The raw material was donated by the educational institution itself, free of charge. As it did not involve Brazilian biodiversity, because the banana constitutes a broad spectrum of species native to Asia and introduced into the country, there was no need for ethical-legal registration in the Genetic Heritage System of the Ministry of the Environment in accordance with Law no. 13,123/2015 (Brasil 2015). The use of microcrustaceans in bioassay, as it does not fall into the category of tests with chordate animals, also did not require bioethical assessment for its management and use, in accordance with Law no. 11,794/2008 (Brasil 2008). As the object of the research did not involve human beings, there was no need for assessment by an ethics committee, as provided for in Law no. 14,874/2024 (Brasil 2024).

Scenario and sample

The primary locus of the study was a university restaurant in the city of Sobral, in the interior of Ceará, northeastern Brazil. The daily service capacity of this FNU provides an average of 1,500 meals for internal users, including lunch and dinner from Monday to Friday. The menu offers two types of proteins of animal origin and a vegetarian option, four types of garnishes, a raw or cooked salad, a dessert (fruit or sweet) and juice. The service system is self-service for all items, except proteins.

Silver banana (*Musa sapientum*) peels were used, obtained from the selective waste available in the university restaurant. The choice was based on the best workability with this by-product, including greater general availability compared to the peels collected from the total daily organic matter and the intention for a prototype synthesis route with fewer steps and more feasible.

The collection of raw materials was carried out weekly, from March to June 2023. Throughout the period, active dissemination of selective collection was carried out on posters, social media and direct instruction to students mediated by scholarship holders in the university restaurant.

Construction of waste utilization indicators

The daily average of the values found for total waste (Kg), the actual sample quantity used for the experiment (Kg) and rest-ingestion (g), as well as the representative cost per student meal (R$1.10) were used to create descriptive statistics, with simple projections in absolute or relative form, over a daily or annual time course. The quantitative indicators generated measured the impact of physical and economic resources on the option for a biological sample.

Banana peel flour processing

The samples were immediately transported to the laboratory processing unit. With due sanitary precautions, the research team refined the separation of samples from other mixed organic remains. The banana peels were sanitized by washing them in running water and disinfected with 0.05% hypochlorite for 10 minutes, dried on common absorbent paper and placed in clean, large plastic containers.

A pilot study was preliminarily conducted to determine qualitatively and quantitatively the best processing aimed at dehydrating the samples. The banana peels were packed non-overlapping and loosely in professional electric food dehydrating equipment (Bom Cultivo, Santa Catarina, Brazil), using automatic programming in one of the three initial protocols with temperature and time control: pilot 1, at 60ºC for 12pm; pilot 2, at 60ºC for 6h and 70ºC for 6h; and pilot 3, at 70ºC for 7h. The dehydrated peels were stored in plastic trays and remained in a laboratory environment. After four weeks, they were crushed and sieved, to observe storage stability. Pilot 4 was carried out, as a replica of the conditions of pilot 3, but in continuous processing without waiting four weeks for flouring, to observe whether there would be a difference in short-term stability. Both the structural aspect and the performance achieved were considered when deciding on the most suitable protocol.

The eleven subsequent batches used the standardized thermal protocol. The dehydrated banana peels were ground in a blender, crushed in a wooden pestle until they obtained a fine particulate flour consistency and underwent simple separation of non-crushable fibrous residues on a domestic sieve with 1mm porosity for minimum homogeneity of the final prototypes. Finally, they were stored in sealed plastic packaging until further laboratory characterization.

Figure 1 summarizes the steps involved in the sustainable obtaining of dehydrated banana peel flour.

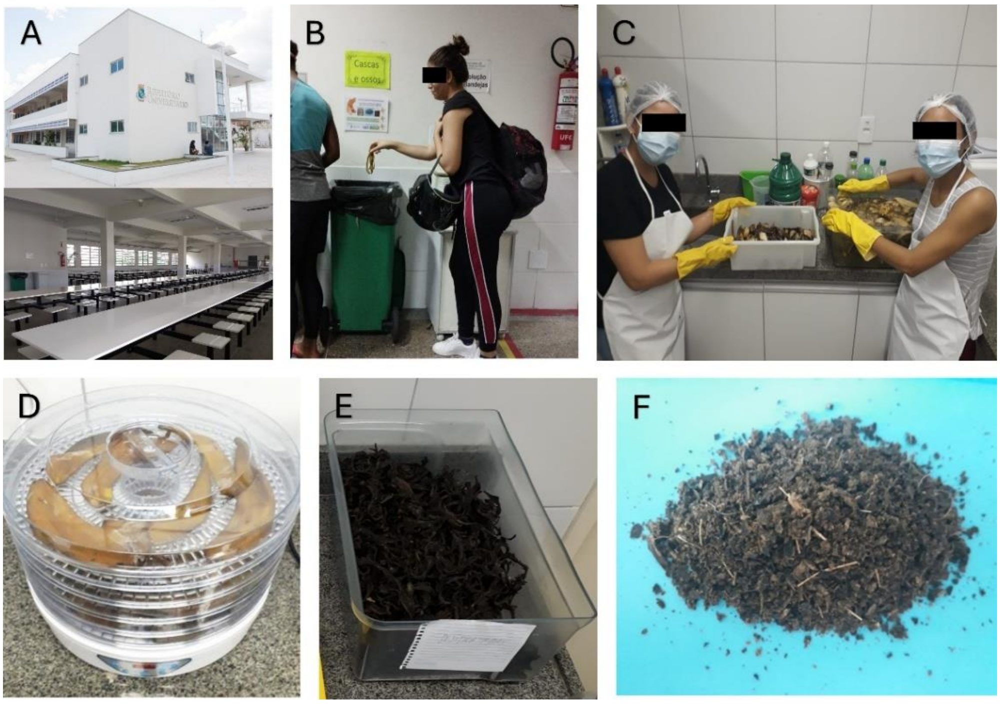

Figure 1. Production of banana peel fertilizer. Samples from the university restaurant (A) separated from selective collection (B) go to the laboratory for sanitization (C), dehydration (D) and after drying (E), they are crushed to generate a flour product (F). Source: Research data.

Production yield analysis

An initial weighing of the banana peels was carried out, with the wet matter of each sample on the day of collection and final weighing of the flours, with the dry matter obtained after processing was completed. The relative calculation, obtained by the ratio of the weight of dry matter in grams divided by that of wet matter in grams multiplied by 100, generated individual values and total mean ± standard deviation expressed as a percentage of mass, allowing the analysis of each pilot's performance or batch of flour.

Micromorphological and sensory analysis

Banana peel flours were analyzed with a trinocular stereomicroscope model DI-106T (Digilab, Sao Paulo, Brazil) attached to digital camera model NewValue 48 Megapixel (Panasonic, Sao Paulo, Brazil) at final magnification of 100x the actual size of the samples. As general micromorphological aspects, particle shapes, sizes and homogeneity were examined.

Additional macroscopic organoleptic characteristics, such as color, consistency, noise and smell, were correlated to the microscopic data to trace the morphofunctional profiles of the pilots and contribute to the choice of the best processing protocol.

Biochemical composition analysis

The colorimetric method was used to detect the presence of primary plant macronutrients ammonia nitrogen, phosphorus and potassium (NPK) and pH in fertilizers. Three different batches of experimental banana peel fertilizer were considered for this test, according to the progressive production scale (batch #1, #6 and #11). Two commercial controls were used, a mixed mineral compound NPK 4-14-8 Jardim (Forth, Sao Paulo, Brazil) named NPK1 and a complete garden fertilizer NPK 10-10-10 (Heringer, Sao Paulo, Brazil) named NPK2. Distilled water was considered as the blank without fertilizer.

Quantities of 1g of fertilizer samples were diluted in 5mL of distilled water in a test tube, homogenized in a vortex shaker (Kasvi, Parana, Brazil) in the short-time touch function, with vibration of 2,800 rpm for 30 seconds, keeping rest in position vertically for 30 minutes at room temperature, until two distinct phases appear. For each test of NPK and pH standards, 0.3mL of the supernatant was transferred to an Eppendorf tube and the precipitate discarded. Each homogeneous liquid was analyzed by the Soil Test Kit (Catkins, Sichuan, China), by adding a drop of the coloring reagent (potassium extractant solution or phosphorous extractant solution or pH test solution or ammonia nitrogen activator), and the solution was stirred again and remaining in contact for 30 seconds to reveal phosphorus and potassium and 1 minute for ammonia nitrogen and pH. Furthermore, the ammonia nitrogen solution was added for the nitrogen test, which reacted over 15 minutes. Each final reaction was read based on a specific color scale for each parameter. Each parameter per group was tested in quintuplicate.

Ecotoxicity assay for Artemia salina

In an aqueous solution with sea salt at a concentration of 30 g/L, pH between 8.0 and 9.0 and with constant aeration at 25ºC, dehydrated cysts of *Artemia salina* (Aquamante, Sao Paulo, Brazil) were incubated for 48h until they hatched. Around 10 young forms (larvae or nauplii) were transferred using manual pipettes to 1mL wells of 24-well plastic plates containing the aqueous extract of the diluted samples to be tested, at the following concentrations: 10, 100, 1,000, 10,000 and 100,000μg/mL (or ppm). Saline water was adopted as a negative control and potassium dichromate (VETEC Quimica Fina Ltda, Rio de Janeiro, Brazil), a chemical agent with expected toxicity, was adopted as a positive control. Each concentration per group was tested in quadruplicate.

After incubation at room temperature for 24h and with visualization using a stereomicroscope model DI-106T (Digilab, Sao Paulo, Brazil), the percentage of corrected mortality was calculated, considering live and dead nauplii, non-phototropic or immobile, using the formula Abbott (Eq.1), where:

$$\text{Mortality (\%)} = \frac{Treatment\ mortality - Control\ mortality}{100 - Control\ mortality} \times 100 \qquad \text{(Eq.1)}$$

Statistical analysis

Parametric data were tabulated in Excel (Microsoft Office 365, USA). Differences between groups were graphically represented and analyzed by inferential statistics using Jamovi software version 2.3.28.0 (Jamovi Project, Sydney, Australia). The data distribution was subjected to the Shapiro-Wilk test and once its non-normality was confirmed, the non-parametric Kruskal-Wallis test and the Dwass-Steel-Critchlow-Fligner multiple comparisons post hoc test were applied, considering a 95% confidence interval and significant differences if $p<0.05$.

Results

Banana peel as an economical raw material

When considering that each meal weighs an average of 450g, a value compatible with the individual consumption of a young adult, a total of 675kg of food was available daily. Based on recorded discards, the daily average of food remains left on diners' plates (rest-ingestion) mixed with paper and plastic (dry residues) stored in general organic waste added to the selective collection of bones and shells in exclusive bins and trimmings of food from the meal preparation area (counter leftovers) was around 55kg. In a relative calculation of quantity, the percentage of solid waste was equivalent to 8.15% of the total food. In a temporal projection calculation, based on the average of 21 working days, 10 months of academic period and 210 days of annual activity at the FNU, a total production of solid waste is expected to be around 11.55 tons per year. When calculating the rest-ingestion or consumption per meal, total waste disposal is equivalent to 55g. Given the symbolic value of the meal of R$1.10 for FNU students, the monetization of daily waste would be equivalent to R$134.44.

The 15 sample collections in this study counted 79.561 kg of bananas, making a daily average of 5.304 kg, which represents 9.64% of the total daily waste. The monetization of this use would be equivalent to R$12.97 per day. Although these are modest values, when making an annual projection, the total amount of bananas originating from this FNU would have a reuse of 1.113 tons and R$2,723.70 wasted per year. In this way, bananas can be validated as an ecological and economic strategy, representing a low-cost sample, reducing institutional investment in raw materials and reducing waste, and adding value in the generation of a new bioproduct.

Standardization of dehydration generates better quality flour

Tests with dehydrated banana peels under different protocols demonstrated better performance with heat treatment at higher temperatures. Pilots 1 and 2 generated flours with higher yields (Table 1).

Table 1 – Differences in yield according to the thermal processing of banana peel flours.

Condition	Initial weight	Dehydration	Grinding and Sieving	Final weight	Yield
Pilot 1	3,361 g	60ºC, 12h	In 4 weeks	557 g	16.57%
Pilot 2	4,902 g	60º C, 6h + 70 º C, 6h	In 4 weeks	642 g	13.10%
Pilot 3	8,118 g	70ºC, 12h	In 4 weeks	874 g	10.77%
Pilot 4	6,940 g	70ºC, 12h	Immediate	703 g	10.13%

Source: Research data.

Regarding morphological aspects, pilot 1 and 2 exhibited a darker color, larger, more heterogeneous granules with a mixed appearance, from prismatic to amorphous patterns, in addition to long trace fibers related to their fibrous consistency. These conditions showed greater softening to the naked eye, related to spontaneous rehydration upon contact with atmospheric air, which made the crushing process more difficult. In pilots 3 and 4, despite the lower yield between dry and wet weight, the samples demonstrated better dehydration, due to a darker, crackling and friable appearance, with smaller particles, a mixed appearance, from cuboidal polyhedral to amorphous, and more homogeneous, without differences between them in terms of their morphological structures (Figure 2).

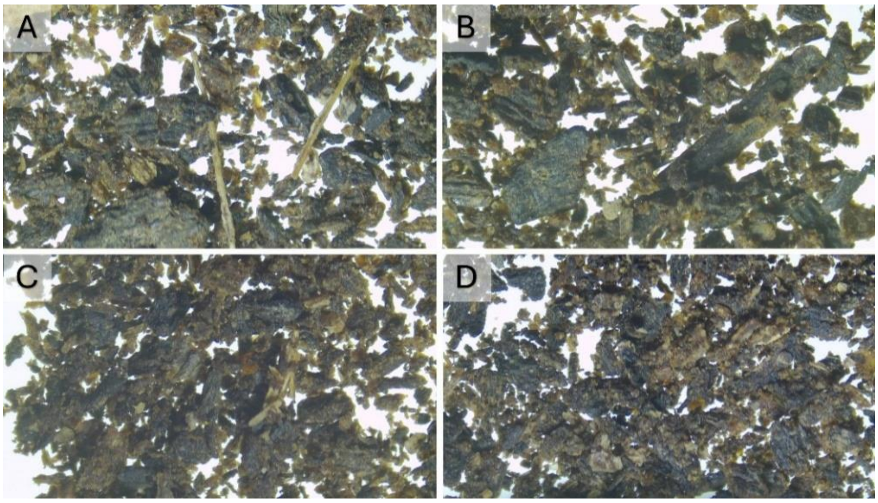

Figure 2 . Morphological aspect under stereomicroscope of banana peel flour pilots under different synthesis routes: pilot 1 (A), 2 (B), 3 (C) and 4 (D).
Source: Research data.

No pilot had a bad odor. As the last processing (pilot 4) was continuous, it was considered more operationally advantageous and adopted as a standard for sample reproducibility in subsequent tests.

Yield predictability of banana peel flour

The eleven collections carried out during the study maintained the yield predictability observed in the pilot study. There was a substantial reduction in the volume of samples, based on the weighing of wet matter ranging from 3,100g to 8,018g and dehydrated flour from 349g to 786g. The yield reached a range of 9.48% to 11.62%, with a total average of 10.31% and an approximate standard deviation of 0.01% (equivalent to 0.006486) (Table 2).

Table 2. Analysis of the yield of different batches of banana peel flour.

Condition	Initial weight	Dehydration	Final weight	Yield
Batch 1	8,018 g	70º C, 12h	786 g	9.80%
Batch 2	5,182 g	70º C, 12h	553 g	10.67%
Batch 3	4,766 g	70º C, 12h	478 g	10.03%
Batch 4	6,915 g	70º C, 12h	682 g	9.86 %
Batch 5	5,620 g	70º C, 12h	533 g	9.48%
Batch 6	5,600 g	70º C, 12h	651 g	11.62%
Batch 7	4,450 g	70º C, 12h	452 g	10.16%
Batch 8	4,300 g	70º C, 12h	436 g	10.14%
Batch 9	3,100 g	70º C, 12h	349 g	11.26%
Batch 10	3,600 g	70º C, 12h	357 g	9.92%
Batch 11	4,689 g	70º C, 12h	491 g	10.47%

Source: Research data.

High mineral and alkaline content in banana peel flour

The nitrogen concentration of banana peel flours was like NPK1, which followed a small range between 18 and 26mg/L, being much lower than the overconcentrated NPK2 (160mg/L), but all fertilizers were higher than distilled water, with zero value. The phosphorus concentration of banana peel flours was like NPK1 and NPK2, ranging from 98 to 112mg/L, and all groups were higher than distilled water, with a value of zero. The potassium concentration of banana peel flours was like NPK1, ranging from 56 to 62mg/L, only batch 11 and NPK1 were higher than NPK2 (32mg/L), but all fertilizers were higher than distilled water, with zero value. The pH value of banana peel flour was like NPK1, ranging from 7.4 to 7.8, with a more alkaline tendency, being higher than distilled water with a pH of 6.2, and NPK2 with a pH of 5.4, with a more acidic tendency. The synthesis of the biochemical parameters of the tested samples is represented in Figure 3.

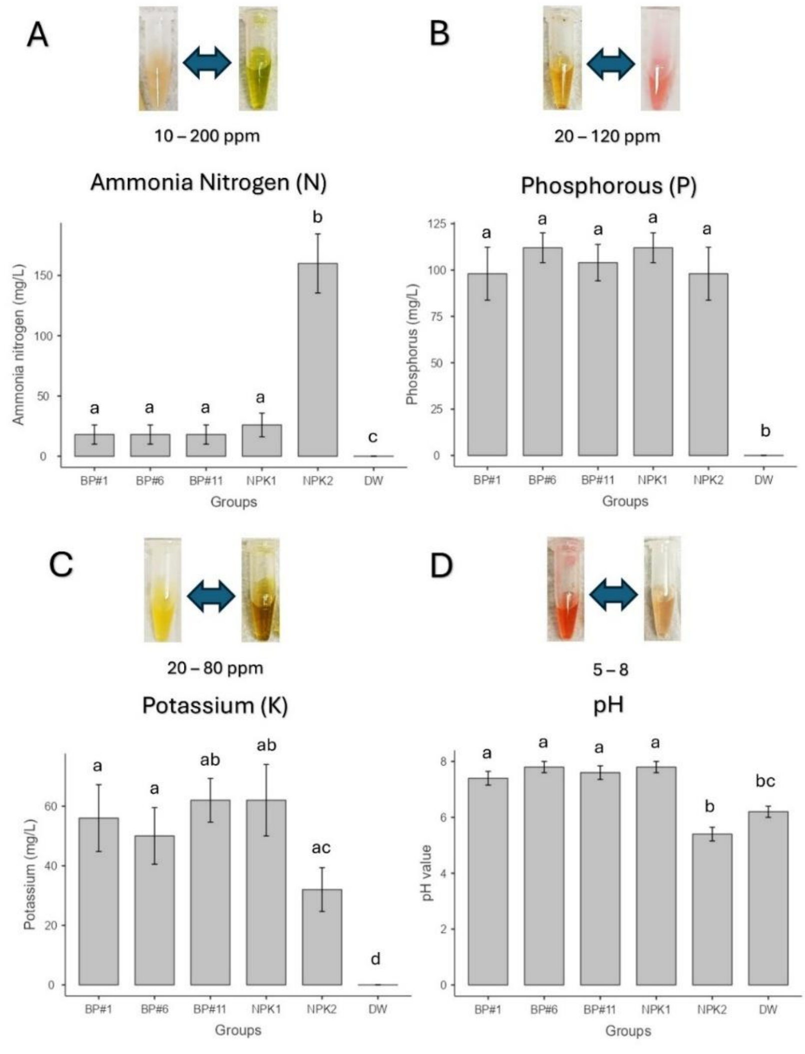

Figure 3. Biochemical analysis of fertilizers (BP#1, BP#6 and BP#11), controls (NPK1 and NPK2) and blank, for ammonia nitrogen (A), phosphorus (B), potassium (C) and pH (D). Means±standard deviations of the compositions with distinct letters indicating significant differences ($P < 0.05$, Kruskal-Wallis test). Source: Research data.

Absence of ecotoxicity in banana peel flour

Concentration-dependent mortality for *Artemia salina* was observed for all groups. All batches of banana peel flour did not exhibit toxicity at the low concentrations tested up to 10,000µg/mL, a concentration where they remained slightly below the 50% of mortality (LC_{50}). Marked toxicity was only observed at a concentration of 100,000μg/mL. There were no significant differences between the batches, but there were differences between banana peel flour and the positive toxicity control ($p<0.05$) at concentrations of 10 to 10,000μg/mL. For potassium dichromate, the LC_{50} would be between 100μg/mL and 1,000μg/mL, which represents a notably toxic standard. Such data show the biological safety of the tested flours. Figure 4 summarizes the ecotoxicity test in the microcrustacean model.

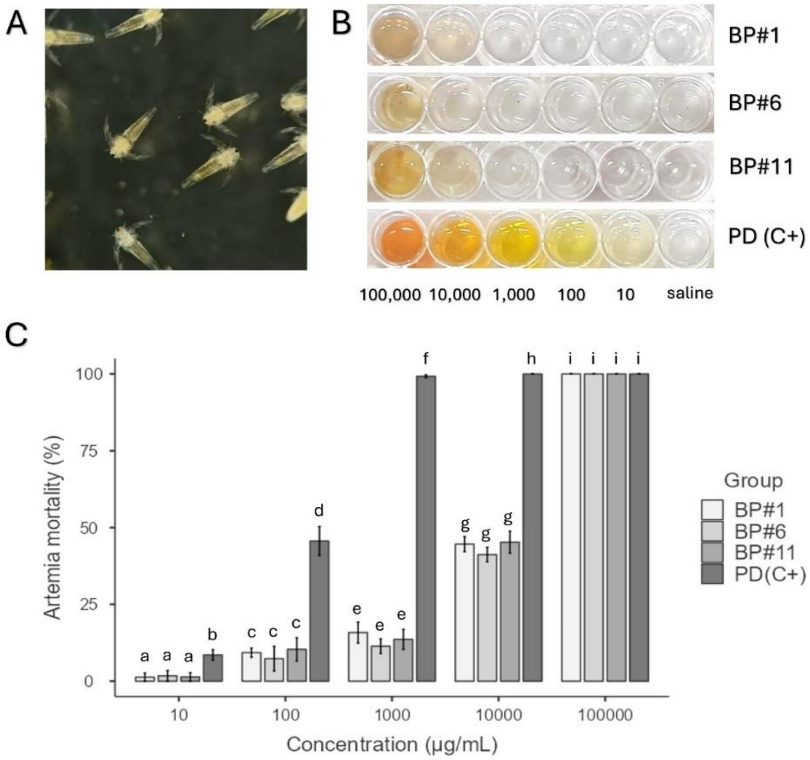

Figure 4 .Fertilizer ecotoxicity analysis. *Artemia salina* nauplii (A) were incubated in different concentrations of potassium dichromate (PD) or batches #1, #6 or #11 of banana peel flour (B). Means±standard deviations of mortality after 24 hours, with distinct letters indicating significant differences ($P < 0.05$, Kruskal-Wallis test) (C). Source: Research data.

Discussion

Mitigation of waste in FNU is justified both by hygienic-sanitary aspects and by economic aspects of cost reduction (Zotesso et al. 2016; Candida et al. 2021). The average generation quantity of 55g of solid waste in the present study is slightly above the rest-ingestion, where per capita values vary between 15 and 45g (Domingues et al. 2016; Ferreira et al. 2023). However, it is similar to the production of rest-ingestion per consumer/meal found by Domingues et al. (2016) with 60.8g, Deliberador et al. (2021) with 68g and Forner and Conto (2020) with 77g, although it is close to twice the values of Ferreira et al. (2023) with 36g for lunch and 25g for dinner and a third of that found by Carneiro (2013), with an excess of 200g, showing that the challenges of reducing waste production are common in FNUs in Brazil. The rest-ingestion of 8.15% found is considered good, within the range of 5 to 10% according to Zotesso et al. (2016) or regular, within the range of 7.6 to 10% according to Silva et al. (2021a). The monetization of daily solid waste of R$134.44 appears to be much lower than that found in the literature, with values for remaining intake of R$429.83 at lunch and R$711.32 at dinner by Ferreira et al. (2023) and an average/day of R$612.71 per Carneiro (2013).

It is important to recognize the influence of variables that influence the general disposal of FNU food, including: lower consumer acceptability, as verified by Deliberador et al. (2021), Silva et al. (2021a) and Forner and Conto (2020), greater supply than demand for food and liquid intake with a meal, as suggested by Forner and Conto (2020) or even the eating shift, where lunch generates much higher waste than breakfast according to Silva et al. (2021a) or dinner and supper according to Borges et al. (2020). In the case of banana peel, the production of this raw material is constant in the FNU (Silva et al. 2021c). It must be considered that bananas are among the three most consumed fruits in the world and their annual production reached 115.74 million tons according to Barnossi et al. (2021). In Brazil, bananas are the second most cultivated fruit after the oranges, with the country being the fourth largest banana producer, with 8.5% of the world's generation, and its largest consumer (Pessoa 2009; Neris et al. 2018). Also, according to Pessoa (2009) and Neris et al (2018), given the great waste of bananas, where it is estimated that up to half of the quantity produced could be lost until it reaches the consumer because it is perishable, urgent strategies must be considered for use of its by-products. Borges et al. (2020) defended the concept of Resource Based View where there is the development of sustainable competitive advantages through the creation of value, in a way that is difficult for competitors to imitate. When applying the assumptions of Borges et al. (2020), where the constancy of unique resources confers an inelasticity of supply and novelty to the proposal, the wide availability of banana peel in the analyzed FNU would benefit its bioprospecting as a fertilizer.

Mapping waste generation processes is important to identify demands and implement improvements (Borges et al. 2020). Selective collection requires establishing an organizational flow, standardizing steps, rules and team training (Zotesso et al. 2016; Menezes & Anjos 2017; Rodrigues et al. 2019). Silva and Souza (2019) suggested the sequential steps of minimization, segregation, storage and final disposal of waste for good solid waste management. Forner and Conto (2020) highlighted that knowledge of its gravimetric composition, distinguishing organic matter from other items, makes the destination of waste more assertive. Unfortunately, separating the banana peels from the waste intended solely for them required more time and effort than initially expected by the research team, crediting this phenomenon to the users' lack of culture of environmental awareness and the still little value given to them to selective collection. To promote better use of natural and technological resources, it is necessary to develop a technological roadmap (Bathmanathan et al. 2023). The valorization of banana peels as a natural biological input, without chemical additives, reinforces the benefits of a sustainable production chain with a clean production line (Borges et al. 2020).

Automatic composting equipment promotes better control of temperature, agitation, microbial activity and air flow, as well as a significant reduction in process time, from 6 to 8 weeks to 24 hours according to Candida et al. (2021) and weight, to half to one third of the original observed by Bathmanathan et al. (2023) or up to a fifth of the original according to Candida et al. (2021), which is closer to the performance found in this study. According to Candida et al. (2021), conventional composting encompasses an active degradation phase, thermophilic between 45 and 65ºC in aerobiosis that lasts weeks and a maturation or curing phase, mesophilic below 45ºC until room temperature, when humidification occurs. Some factors can interfere with composting, where biomasses composed of a lot of carbon and little nitrogen degrade less, the stirring releases oxidation heat as water vapor, generating undesirable humidification and heterogeneity in the substrate and the spacing between the particles allows better passage of oxygen (Candida et al. 2021). Neris et al. (2018) tested natural drying of silver banana peels at 35ºC for three days and the humidity decreased from 81 to 91% to 18 to 24% and the ash content increased from 1 to 4% to 13 to 14%. Pessoa (2009) observed 86% humidity and 1% ash in natural silver bananas, while convective drying of silver banana peels between 40ºC and 60ºC for up to 160 minutes promoted higher quality of the flours, with humidity from 4 to 5% and ash from 7 to 9%. The option for a more intense dehydration protocol, instead of composting, with a high temperature in a shorter time (70ºC for 12h), without stirring thin samples, which are no longer in contact for good air circulation, was justified by the intention of limit biotic interference and degradation of the base structure of the samples, keeping them better preserved for nutritional preservation until flouring. The processing results corroborate Pessoa (2009), who suggested that the conversion to a darker color and hardening of the samples indicate the final drying point and a longer shelf life of the product. Darkening may also indicate the sugar content in contact with temperature, favoring Maillard reactions or non-enzymatic browning (Neris et al. 2018).

In composting, there are initial changes in the biomass, with the release of toxic substances such as mineral acids and few nutrients, until it becomes more basic and biodegradable, with chemical, physical and biological properties ideal for a fertilizer (Candida et al. 2021). Nitrogen fell short of the range of Acevedo et al. (2021), as well as below 12.5g/kg (or 12,500ppm) found by Barnossi et al. (2021) or 10.21% (or 102,100ppm) found by Mustapha et al. (2021), but still, it was well above the value found of 0.56mg/kg (or 0.56ppm) by Adrija and Navni (2018). Higher nitrogen composition, such as that found in household waste, accelerates decomposition (Candida et al. 2021). On the other hand, the low concentration of nitrogen in banana peel flours compared to commercial fertilizer 2 may therefore suggest slower degradation, which would be an advantage.

The average levels of phosphorus and potassium found were like the biochemistry expected in dried banana peels described by Acevedo et al. (2021) and Adrija and Navni (2018). Some studies showed a lower amount of phosphorus in dried banana peels, such as 0.23mg/100g (or 2.3ppm) according to Acevedo et al. (2021) and 2.95mg/kg (or 29.5ppm) according to Adrija and Navni (2018), while others claimed better preservation of phosphorus in samples, such as El-Serafi et al. (2023) with 169.2mg/100g (or 1,692ppm) and Mustapha et al. (2021) with 26.7% (or 267,000ppm). Drawing a comparison with calcined bone fertilizer, the amount of phosphorus also remains lower, compared to the discrepant concentration of 34 to 41% (or 340,000–410,000ppm) found by Nascimento et al. (2025). The amount of potassium in banana peel according to various analytical tests is generally high, such as 5.10% (or 51,000ppm) by Mustapha et al. (2021), 78.1mg/g (or 78,100ppm) according to Ansari et al. (2023) and Howeidi et al. (2023) or >100g/kg (or 100,000ppm) by Barnossi et al. (2021). Pessoa (2009) stated that banana peel has more nutrients than the pulp or edible part, with the amount of potassium varying from 81.11 to 143.78mg/100g (or 811.1–1,437.8ppm) in natura for 623.91 to 845.74mg/100g (or 6.2391–8.4574ppm) of the overconcentrated dehydrated sample. Much more discreet values, from El-Serafi et al. (2023) with 5.36mg/100g (or 53.6ppm) and Adrija and Navni (2018) with 299mg/kg (or 299ppm), were closer to the profile of the samples in this study.

The pH remained alkaline, even slightly below the range above 8 recommended by Adrija and Navni (2018), Acevedo et al. (2021) and Mustapha et al. (2021). The fact that pH had an alkalizing tendency in banana peel flour makes the option for the dehydration technique more important, which converges with the curing phase of composting (Candida et al. 2021). Neris et al. (2018) compared fresh versus dried banana peels at room temperature and noticed a drop in pH, from the range of 7.17-7.84 to 5.71-6.84, respectively. Pessoa (2009) compared natural silver banana peel versus dried at 70ºC and noted pH stability (from 5.67 to 5.56), despite remaining acidic, which contrasts with previous citations. Barnossi et al. (2021) found a pH of 6.23 in dried banana peels, which, although higher, remains less than desirable. This reinforces the importance of this study, which achieved a favorable basic pH. Continued research on dried banana peels is stimulated by phytochemical analyzes, which confirm the presence of antioxidant agents, in addition to phenolics and flavonoids proven by Okolie et al. (2016) and carotenoids, biogenic amines, polyphenols, phytosterols, flavonoids and antioxidants observed by Bhavani et al. (2023), which protect plants from different biotic and abiotic stresses (Okolie et al. 2016; Bhavani et al. 2023).

According to Candida et al. (2021), the initial phase of composting is phytotoxic, with the production of substances harmful to plants, requiring safety testing. In the search for biological testing for fertilizers, the *Artemia salina* model has been used since the 1980s and is internationally recognized for ecotoxicological analysis of nanomaterials, justified by its sensitivity to agrochemical contaminants, importance at the base of the food chain and ease of laboratory cultivation (Meyer et al. 1982; Hamidi et al. 2014; Ayoub et al. 2023). The concept of a toxic product in small concentrations can vary, up to 100ppm according to Zailani and Sharkawi (2019), moderately toxic from 100 to 500ppm, slightly toxic from 500 to 1,000ppm according to Vergara and Riquelme (2019), and it is well established that 1,000 ppm is the most used cutoff point, indicating the absence of toxicity beyond this range (Meyer et al. 1982; Sumathi et al. 2011; Vergara & Riquelme 2019). Ayoub et al. (2023) tested three fertilizers and demonstrated different toxicities, depending on the highest concentration of nitrogen, as observed with ammonium sulfate and its LC_{50} of 37.32mg/L (or 37.32ppm) and ammonium nitrate and its LC_{50} of 110.32mg/L (or 110.32ppm) when comparing with the mixture of nitrogen 10%, phosphorus 30% and potassium 10% and its LC_{50} of 143.13mg/L (or 143.13ppm). Nascimento et al. (2025) tested fertilizers from bone ashes, rich in phosphorus and recorded LC_{50} of 4,771 to 6,194ppm with calcination for 2h and LC_{50} of 12,402 to 78,098 with calcination for 4h. Such evidence shows that the tested biofertilizer is more like the profile of phosphates than nitrogen, representing a safe alternative to conventional fertilizers.

From banana by-products, different mortality reasons for *Artemia salina* are found in the literature. Zailani and Sharkawi (2019) tested essential oils obtained by hydrodistillation of dried shells of Musa spp. and a dose-dependent lethality associated with ether and alcoholic groups, with LC_{50} greater than 100ppm, which are then considered non-toxic. Vergara and Riquelme (2019) tested hydroalcoholic extracts from Musa spp. leaves and found LC_{50} lower than 1000ppm, ranging from low to moderate toxicity, with greater toxicity associated with higher phenol and flavonoid content. Chakraborty et al. (2018) testing green leaves of *Musa paradisiaca* reached an LC_{50} of 0.845 μg/mL (or 0.845ppm), which demonstrates high toxicity in natura. Hamidi et al. (2014) with extracts from *Musa paradisiaca* reached an LC_{50} of 15.10mg/mL (or 15,100ppm), despite the lack of location specificity of dry biomass, be it roots, bark, branches, stipules, leaves, flowers, fruits or whole plant. Chowdhury et al. (2016) studied dry roots of *Musa paradisiaca* and found toxicity with an LC_{50} of 22.336μg/mL (or 22.336ppm). González et al. (2020) tested liquid extract of *Musa acuminata* sap and reached LC_{50} at a concentration of 22.553% (or 225,530ppm). Studies with aqueous extract of banana flower from *Musa acuminata* found an LC_{50} of 7.8mg/mL (or 7,800ppm) and classified as a nontoxic substance by Kartikaningsih et al. (2021) while Sumathi et al. (2011) found a higher LC_{50}, equal to 9.97mg/mL (or 9,970ppm). Logarto-Parra et. al (2001) demonstrated that extract from the trunk of *Musa paradisiaca* had a harmful LC_{50} of 15.10μg/mL (or 15.10ppm), which represented toxicity like artemisia, greater than chambá, clove basil, allspice and mint and smaller than aloe, sour orange, basil, rue and lemongrass. Banana species, location of biomass extraction and physical state after processing are shown to be factors influencing toxicity, requiring more safety studies for banana peels, which are still incipient in literature.

Wazir et al. (2018) found separately per pot that eggshell powder (45g), banana peel (20g) and tea waste (15.9g) were the best sources of organic fertilizer for potato and pea cultivation. El-Awadi et al. (2021) identified that 10g per pot of banana peel powder alone provided greater relief from the deleterious effect of water deficit on soybean plants than potassium sulfate at 1.35g or 2.70g, increasing photosynthetic pigments, plant growth and yield of seeds. This leads us to believe that a high dose of banana peel or hybridization would be necessary to obtain better results. Dayarathna and Karunarathna (2021) evaluated different fruit peel powders as natural fertilizers in okra growth and observed better results with the compound of orange and banana (1:1) than that of banana alone or banana and pomegranate (1:1), in relation to plant height, number of leaves, leaf area, chlorophyll content, days to flowering, dry mass of leaves, stem, root and fruit, length and circumference of the fruit. Fernando and Seran (2023) found that the combined application of banana peel and Moringa leaf powders (1:1) could improve the composition and yield of green grass seeds with less environmental impact.

Mercy et al. (2014) had better results with a fertilizer composed of pomegranate, orange, lemon and banana peel powders in a smaller quantity of 1g/pot than in a larger quantity of 3 g/pot for fenugreek cultivation. Mishra et al. (2023) proposed the use of banana peel and cyanobacteria biofertilizer for sustainable agriculture. Raj et al (2021) demonstrated that powdered banana peel fertilizer can carry plant growth-promoting rhizobacteria, increasing the germination and productivity of rice crops. Nordin et al. (2022) developed an organic fertilizer from banana peel, eggshell and yeast (1.6:6:1) for growing peppers. Such evidence contributes to validating the broad spectrum of synergies and biotechnological potential of banana peel fertilizers, stimulating research applied to vegetable crops.

Ecodevelopment, heterodox to neoclassical economics, involves interdisciplinary and in-depth discussions in the epistemological, theoretical and political spheres for the defense of ecology and human values in collective praxis (Fernandez 2011). Environmental education favors sustainable development, as it supports the shared management of organic solid waste and the awareness of users and employees of a FNU for the success of the process (Carneiro 2013; Domingues et al. 2016; Rodrigues et al. 2019; Candida et al. 2021; Ferreira et al. 2023). Proposals that value collective planning for a circular economy are the new compliance trend in institutions, based on contemporary ESG principles (Borges et al. 2020; Bathmanathan et al. 2023). Furthermore, the Green Metric methodology created by the University of Indonesia evaluated sustainable actions carried out by universities around the world, based on infrastructure, energy and climate change, water, waste management, transport system and education and showed that such criteria they were inseparable (Candida et al. 2021). As the dehydration of banana peels required intermittent electrical consumption for 12 hours, it is necessary to measure the carbon footprint related to the process, which was not the subject of the present study.

The experience with banana peels is a very promising path, which supports teaching, research, extension and entrepreneurship for environmental sustainability, as foreseen in the institutional development plan (Universidade Federal do Ceará 2023). To ensure the continuity of this new production chain, it will be a useful effort to increase awareness campaigns regarding selective disposal in the FNU supported by the user community, as suggested by Carneiro (2013), Domingues et al. (2016), Rodrigues et al. (2019), Silva and Souza (2019), Deliberador et al. (2021) and Ferreira et al. (2023). According to Balafoutis et al. (2020), in the new technological trends of smart agriculture, it is necessary to measure the effects of generating a product from an economic and environmental point of view, and the development of banana peel biofertilizer and its initial testing of composition and biological safety in an environment laboratory would fit into technological maturity level four.

Therefore, new product validation tests in a relevant and operational environment must be carried out to overcome the limitations inherent to the design of this study. As future perspectives, analyzes of biofertilizer performance in different types of soil and agricultural crops could be proposed to investigate plant growth and nutrient retention over time; analysis of product stability during storage in different humidity and temperature conditions; and other validation and scalability analyses, so that banana peel flour is consolidated as a sustainable and efficient solution for waste management and soil fertilization.

Conclusion

Banana peel biofertilizer exhibits sustainable development potential, with simplified processing, predictable yield, mineral abundance, alkalizing tendency and non-toxicity. Future application studies on different vegetable crops in green areas on the campus should be conducted to verify their effectiveness in situ, as well as the impact on environmental compliance of the endogenous demand for waste at the university.

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