American Journal of Sciences and Engineering Research www.iarjournals.com

American Journal of Sciences and Engineering Research

E-ISSN– 2348–703X, Volume 9, Issue 1, 2026

Environmental and Economic Assessment of Banana Production and Processing in The Tucuruí Lake Region, Amazon

Joana C. Z. Pinheiro

Rural Federal University of Amazônia UFRA, 68.515-000 –, Parauapebas, PA, Brazil. Email: joanazandonadi@yahoo.com.br

André L.A. Mesquita

Amazon Development Center in Engineering – NDAE, Federal University of Para, 68.455-901 – Tucuruí, PA, Brazil. Email: andream@ufpa.br

Luiz Moreira Gomes

Institute of Exact Sciences. University of South and Southeast of Pará, 68507-590, Marabá – PA, Brazil. Phone: (094) 2101-5900 e Fax: (094) 2101-5901, Email: luizmg@unifesspa.edu.br

Highlights

- Comprehensive life cycle analysis identified key environmental and economic factors in banana farming.
- Use of rainwater for irrigation and reduced synthetic inputs can increase sustainability and profits.
- Value-added banana products showed profit margins above 50% and rapid break-even for small producers.

Abstract: *This study presents a comprehensive Life Cycle Assessment (LCA) of banana production in the Tucuruí Lake region of the Brazilian Amazon, evaluating environmental impacts, economic performance, and sustainability indicators. Data collected from three representative farms were used to quantify key metrics, including an average water footprint of 134.20 m³/ton, carbon emissions of 0.214 kg CO_2-eq/kg (with diesel and fertilizer use as major contributors), and emergy values reaching up to 8.27×10^{17} seJ/year. Additionally, the economic viability of banana by-products—candies, flour, and chips—was analyzed, showing profit margins of up to 51% and breakeven points achievable in less than two months. The study highlights opportunities for improvement, such as rainwater reuse for irrigation, reduced synthetic inputs, and better logistics to lower fuel consumption. These findings demonstrate that integrating environmental and economic strategies can enhance sustainability and profitability in banana supply chains. The research advocates public policies and financial support to empower small producers, promote vertical integration, and advance a circular economy model in Amazonian agriculture.*

Keywords: *Banana; Life Cycle Analysis; Environmental impacts.*

I. Introduction

Society seeks alternatives to preserve the environment and reduce impacts such as resource depletion, species extinction, and climate change. Globally, around 1.4 billion tons of food waste are generated yearly (Sarangi et al., 2022), with the USA discarding 40 million tons annually (Yadav et al., 2021).

 Received-27-12-2025 Accepted- 06-01-2026

Brazil faces challenges in banana exports, including insufficient government support, poor infrastructure, and reliance on the European market (Bornal et al., 2021). Despite being a top global producer, its exports are limited due to diseases and competition with companies like Dole and Chiquita (Ploetz & Ma, 2023).

Global banana production reaches approximately 155.2 million tons, led by India, China, and Indonesia (Ajay et al., 2020). Brazil produces around 7 million tons, but Ecuador is the largest exporter (Jangam & Singh, 2021). In 2017, Brazil ranked fourth in production, while the top importers were the EU, USA, Russia, and Japan (FAO, 2021).

Figure 1: Global Banana Production by Country. Source: FAO Stats, 2021.

Table 1 summarizes global banana production data and each country's significance in the industry.

Country	Production (million tons)	Global Production Share (%)	Notes	Source
India	30,8	29	Largest producer; primarily domestic consumption	Ajay et al. (2020)
China	11	7,1	Second largest producer; primarily domestic consumption	Ajay et al. (2020)
Indonesia	8	5,2	Third largest producer; primarily domestic consumption	Ajay et al. (2020)
Brazil	7	4,5	Most production consumed domestically	Ajay et al. (2020)
Ecuador	6	3,9	Largest exporter; about 28% of global exports	Jangam & Singh (2021)

Table 1: Global Banana Production by Country (Ajay et al., 2020; Jangam & Singh, 2021)

According to FAEPA (2021), Pará ranks as Brazil's 8th largest banana producer, with an annual output of 381,248 tons across 33,662 hectares. Production is concentrated in the Transamazon region, which accounts for 38.27% of the state's total. The main varieties grown include Prata, Mysore, Nanica, and Branca. Despite its significance, the state faces logistical challenges, with only 6% of production reaching Belém.

This study employs Life Cycle Assessment (LCA) to examine banana production around Tucuruí Lake in Pará State (Fig. 2). Data was collected from three farms, including the area's largest producer, to analyze and optimize the production process.

The research integrates LCA and economic analysis to assess the feasibility of vertically integrating fresh banana production for sustainable economic growth. It emphasizes separating production costs from family income—a distinction often overlooked by local producers. By evaluating costs, annual revenues, and environmental impacts (e.g., water and carbon footprints), the study aims to enhance economic, social, and environmental outcomes.

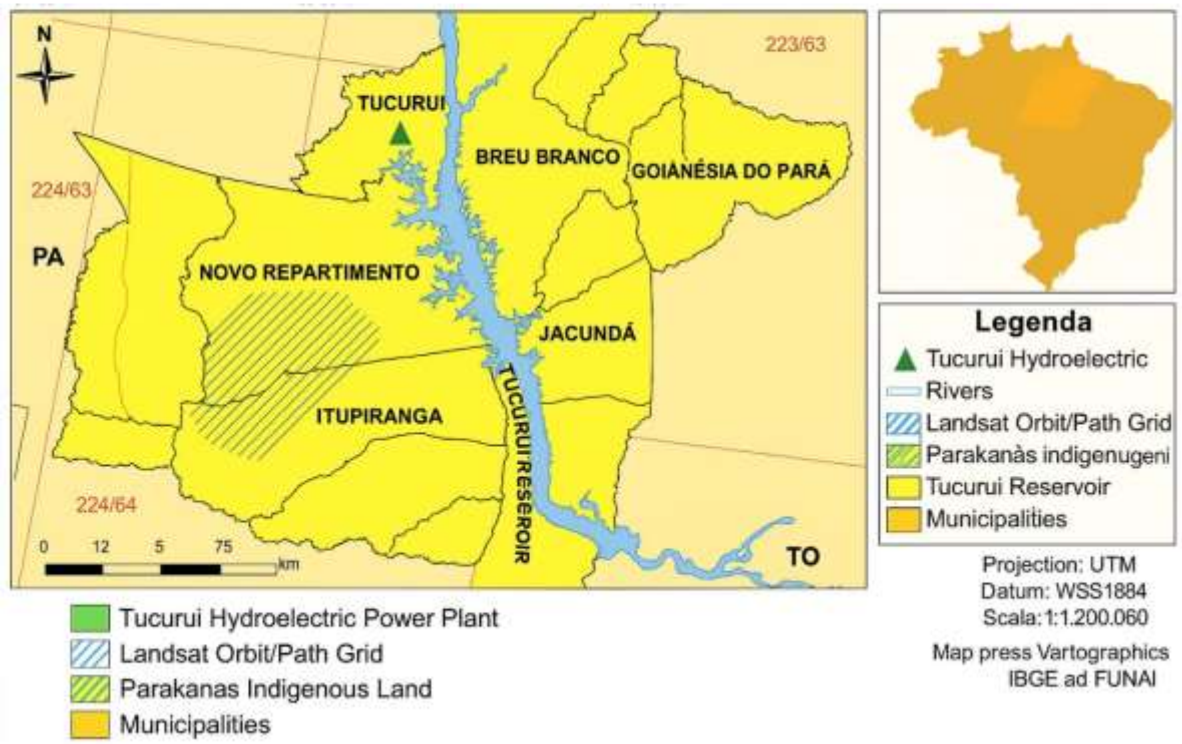

Figure 2 - Location of the study area: the Tucuruí reservoir and the seven municipalities affected by the reservoir.

We collected data on three main properties. The first is the largest banana producer in the Lake Tucuruí region. The second and third properties also possess significant expertise in planting and distribution. As leaders in production, improvements in their processes could serve as a model for other producers in the area.

This paper examines banana production costs, annual revenues, and environmental impacts to improve this region's economic, social, and environmental indicators, resulting in better economic indices in Pará and Brazil.

2. Literature Review

2.1 LCA Studies

Life Cycle Assessment (LCA) is a widely used methodology for quantifying environmental impacts throughout a product's life cycle. In food production, such as banana cultivation, this approach helps identify critical factors influencing sustainability, enabling the implementation of strategies to minimize environmental damage.

2.1.1 **Importance of LCA in Agricultural Production and Environmental Impact Factors**

Life Cycle Assessment (LCA) in agriculture is essential for mapping and understanding environmental impacts from cultivation to commercialization. Recent studies emphasize evaluating agricultural processes based on water footprint, carbon footprint, and energy efficiency (Kallendorf, 2023; Cakmakci et al., 2023). Banana production, like other intensive crops, requires large amounts of water and fertilizers.

Advanced techniques, such as IoT-based precision irrigation and fertilization, have reduced water use by 73% and NPK fertilizer consumption by 50%, though they may decrease yields by 12% (Impact of IoT-Enabled Variable Irrigation..., 2023).

Irrigation systems are a critical factor in banana production's water footprint. Materials like galvanized steel pipes and sand filters have significant environmental impacts due to energy costs and frequent maintenance (Angnes et al., 2023). Agroecological practices, such as mulching and cover cropping, enhance moisture retention and promote more sustainable farming (Traditional Agricultural Knowledge..., 2023).

2.1.2 Carbon Footprint, Waste Management, and Circular Economy

Fertilizer use, transportation, and organic waste management affect banana production's carbon footprint. Improper decomposition of peels releases methane, a potent greenhouse gas (Lisciani, 2024; Sari et al., 2024). Training programs on waste recycling enhance environmental awareness (Sari et al., 2024).
Converting waste into non-activated carbon for bio-lubricants offers a sustainable alternative (Dube et al., 2023). SMEs adopting sustainable models achieve over 40% cost returns with innovative waste practices (Prasetyo et al., 2024).
Processing overripe bananas into food products (cakes, chips) reduces waste and carbon emissions (Fiona et al., 2024). Banana fibers are also used in bioplastics and biodegradable packaging, supporting circular economy principles (Provin et al., 2024; Beram, 2024).

2.1.3 Transportation, Fertilizer Use, and Energy Efficiency

Transportation is a major contributor to banana production's carbon footprint, emitting up to 625.44 kg CO_2-Eq/ton due to fossil fuel use in trucks and refrigerated containers (Pérez-Neira et al., 2020). Alternatives like biogas/hydrogen-powered vehicles and logistical optimization can significantly cut emissions (Machado et al., 2021; Crippa et al., 2021).
Nitrogen-based fertilizers drive N_2O emissions, especially in young plantations (Silva et al., 2022). Optimized fertilization, biochar, and AI-based models can reduce chemical use by 65%, lowering energy consumption and emissions (Kazlauskas et al., 2021; Ramezanpour & Farajpour, 2022).
Despite progress in LCA (Life Cycle Assessment), challenges like methodological variability persist (FAN et al., 2022). Circular bioeconomy strategies, low-carbon tech, and waste valorization are key for sustainable banana production (VÉLIZ et al., 2022).

2.2 The Life Cycle Assessment

Life Cycle Assessment (LCA), governed by ISO 14040 and 14044 standards, is a methodology that evaluates environmental impacts from production to final disposal, including recycling and waste management.
The process consists of four key phases:

1. **Goal and scope definition** - sets study objectives and boundaries;
2. **Inventory analysis** - collects data on all inputs and outputs;
3. **Impact assessment** - quantifies and interprets environmental effects;
4. **Interpretation** - analyzes results and suggests process improvements.

2.3 Calculation of production costs

The Total Cost of Production (TCP) in agriculture encompasses all expenses associated with the cultivation process. It is composed of two main components: the Effective Operational Cost (EOC) and the Indirect Costs (IC). The EOC includes variable costs such as machinery use, labor, and agricultural inputs, covering all activities from soil preparation to harvesting.
On the other hand, the IC refers to fixed costs including land ownership, taxes, and equipment depreciation, as well as expenses incurred before planting and support provided to the farming family. Together, these two categories form the TCP, representing the complete financial commitment required for agricultural production.

$$\mathbf{TCP = EOC + IC} \quad (01)$$

Labor and fertilizers are primary drivers of operational costs in banana production, exerting a direct impact on profitability. Research indicates that the availability of labor and the degree of mechanization significantly influence production costs (Mohiuddin et al., 2022; Rivera et al., 2024). Among inputs, potassium fertilizers—such as muriate of potash (MoP)—and integrated fertilization strategies that combine organic and synthetic sources are known to enhance both yield and soil health (Djohar, 2023; Meya et al., 2023).

Larger farms benefit from economies of scale; although they bear higher absolute costs, they typically achieve superior net returns (Vaishnavi & Khobarkar, 2024). Meanwhile, smallholder farmers—such as those in Brazil—can improve efficiency and reduce expenses through cost management tools tailored to optimize resource use (Bastos, 2021).

Indirect costs, including administrative expenses, maintenance, taxes, and depreciation, also influence the economic viability of banana farming. These costs can vary substantially depending on the allocation method, with labor and machinery components potentially fluctuating by ±35% and ±20%, respectively (Lips, 2017). For instance, a study in Colombia reported that indirect costs accounted for 19.73% of total production costs (Rivera et al., 2024). In India's Wokha district, a cost-benefit ratio of 2.68 was observed, underscoring the profitability of banana farming in that region (Murry, 2019).

2.4. Calculation of economic performance

Several financial categories determine cultivation's economic performance: leveling point or Break-Even Point (BEP), Safety Margin (SM), and benefits/costs ratio (BCR).

The break-even point is when sales are just enough to cover expenses (fixed and variable), in which expenditure is equal to revenue, without a loss or profit. Thus, the Break-Even Point is the stable point of exploration. The relation gives it,

BEP = Total exploration cost / Unit selling price of the product (02)

Determining the break-even point (BEP) is crucial for banana producers as it establishes the minimum production and sales volume needed to cover costs. This analysis enables strategic decisions about optimal planting timing and quantities by assessing the relationship between fixed and variable costs, profit margins, and operational volume. A study of the banana chips company "Berkah Jaya" showed how BEP analysis can set sales targets and prevent losses (Khanifah & Septiana, 2020).

Accurate BEP calculation helps producers align production with market demand and cost structures, minimizing losses and increasing profitability. According to Amanda and Fauji (2024), the safety margin - the percentage difference between actual sales and break-even point - indicates a company's capacity to absorb sales declines before operating at a loss. Thus

SM= (Total Cost of Production – Revenue) / Revenue (03)

The return on investment will be calculated using the relation of Kihal et al. (2021), who measure the overall efficiency as:

Return Rate = Revenue /Total Cost (04)

The return on investment is the business's profit, the higher the rate, the greater the profit.

Productivity

Productivity measures production efficiency in the number of bananas produced per hectare.

$$\boldsymbol{Productivity} = (Total\ Number\ of\ Bananas\ Produced\ (kg)) / \ (Planted\ area\ (hectares)) \quad (05)$$

Cost per Unit Produced

This metric identifies the costs associated with producing each unit of banana.

$$\textbf{Cost per Unit Produced} = (Total\ Production\ Costs\ /Total\ Number\ of\ Bananas\ Produced\ (units)\ ) \quad (06)$$

Profit Margin

The profit margin is the difference between the selling price and the production cost, expressed as a percentage of the selling price (Karipova & Baktybaeva,2023).

$$\textbf{Profit Margin (\%)} = (Selling\ Price\ -(Production\ Cost/\ Selling\ Price\ ) \times 100 \quad (07)$$

2.5. Water Footprint Calculation

The water footprint in agricultural production comprises green, blue and grey components representing different water sources. Green water refers to rainfall consumed by plants, blue water to irrigation use, while grey water is calculated based on applied chemicals and required dilution volume. Recent studies highlight this analysis' importance for sustainable water management, with research in India and Ethiopia showing significant regional variations in these components (Mehla et al., 2023; Hirpa et al., 2023).

N2O emissions in banana cultivation, both direct and indirect, represent a major environmental impact. Mainly resulting from synthetic fertilizers like ammonium sulfate and urea, these emissions vary according to fertilizer type and environmental conditions (Silva et al., 2022; Benghzial et al., 2023). Mitigation strategies include reduced nitrogen use and nitrification inhibitors (Liu et al., 2020; Aguilera et al., 2021). Banana cultivation shows one of the highest fertilization rates per hectare among food crops.

Table 2: Water Footprint Components in Banana Production: Green, Blue, and Grey Water Usage

Green Water	Rainwater stored in the soil	120	R et al., 2024
Blue Water	Surface and groundwater used for irrigation	30	Liu et al., 2024
Grey Water	Water required to dilute pollutants	10	Fatima et al., 2024

Figure 3 is a plot that shows the regional distribution of the water footprint for banana cultivation, with data from different regions, such as Latin America, Southeast Asia, and Sub-Saharan Africa. The plot highlights the variations in the contribution of each type of water in the respective regions, according to the cited studies. This information is essential to understanding the environmental impact of banana production in different geographical contexts and to planning more sustainable agricultural practices.

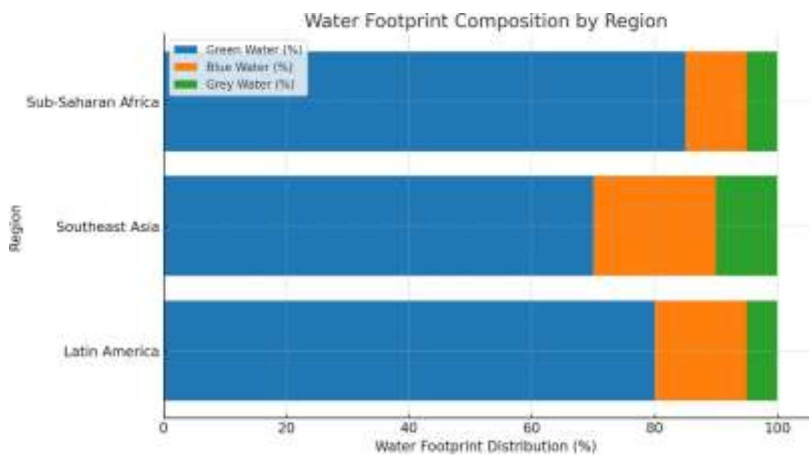

Figure 3: Regional Distribution of Water Footprint for Banana Cultivation

2.6. Carbon Footprint Calculation

The carbon footprint, as defined by ISO 14067 (2012), represents the climate change impact caused by direct or indirect greenhouse gas (GHG) emissions during a product's life cycle. Recent studies confirm this standard remains a fundamental reference for quantifying and communicating GHG emissions, providing a robust Life Cycle Assessment (LCA) framework covering all stages from production to disposal (Smith et al., 2020; Zhang et al., 2021). ISO 14067 complements other standards like ISO 14040 and 14044, ensuring consistency in environmental assessments. Current research highlights the use of modern technologies such as computational simulations to improve emission estimates across industrial scenarios (Johnson et al., 2020; Oliveira et al., 2021). However, challenges persist in data collection and modeling all life cycle stages (Martinez & Ruiz, 2022). GHG emissions are calculated by combining activity data with emission factors, as shown in equation (08).

GHG Emissions = Activity Data x Emission Factor	(08)

The Global Warming Potential (GWP) is a crucial metric for converting greenhouse gas emissions into CO2 equivalents (tCO2e), using the emission factor of 0.0275 as established in Brazil's Second Greenhouse Gas Inventory (MCTI, 2010). Recent studies show that the GWP100 method, assessing impacts over 100 years, is being complemented by alternatives like GWP*, which offers greater accuracy for short-lived climate pollutants like methane. Research by Lynch et al. (2020) proves GWP* reduces methane effect overestimations, while Smith et al. (2021) demonstrated this metric is 35% more accurate than GWP100.

Data from Pressman et al. (2023) in California revealed a 28% improvement in matching simulated emissions with actual impacts when applying GWP*. Kendall et al. (2020) further highlight that time-adjusted warming potentials (TAWPs) can reduce CO2 equivalents by up to 30% by considering specific emission timing. These advances emphasize the importance of alternative metrics for more precise and efficient climate policies.

2.7 Emergy Calculation

The emergy concept, introduced by H.T. Odum, assesses the real value of renewable resources by accounting for all energy invested by nature and human processes, unlike traditional economic assessments that undervalue these resources. Emergy quantifies environmental value based on the biosphere's time and space, showing that renewable resources' actual value is inversely proportional to their market price. It represents the total energy required to sustain a process throughout its production chain, measured as solar energy equivalent embodied in products or services, as shown in equation,

Emergy = Sum of the energy required	(09)

Emergy application in banana production provides valuable sustainability insights by integrating resources, energy flows and environmental impacts. Yang et al. (2021) demonstrate that low-carbon practices reduce emissions and improve resource efficiency, assessing both direct (fossil fuels) and indirect (solar energy, labor) contributions. Emergy analysis identifies inefficiencies and optimizes resource use, enhancing economic and environmental performance. The same study shows social media use increases sustainable practice adoption by 1.1 times.

Transformity, the quantitative variable converting energies to solar equivalents (sej/J), is essential for agricultural sustainability assessment. Odum (1996) established that renewable resources' real value is inversely proportional to market cost. This approach identifies more efficient practices like low-consumption irrigation systems and integrates with LCA to quantify environmental impacts. Recent works (Barros & Silva, 2020; Souza &

Mendes, 2021; Cocampo, 2022) highlight its role in valuing ecosystem services and sustainable policy planning.

3; System description

Banana cultivation involves key steps including soil preparation, plowing, fertilization, and seedling acquisition, crucial for optimal growth conditions. Recent studies show integrated nutrient management, such as intercropping with cowpeas, can increase yields by 15.07% (Sathya et al., 2024). Variety selection is critical, with research focusing on crossing commercial triploids with improved diploids to develop new genotypes (Scherer et al., 2024). Disease control has advanced with AI detection techniques, reducing pesticide use (Thirumeninathan et al., 2024). Figure 4 shows a complete production flowchart from soil preparation to commercialization, including irrigation, cultivation practices, harvest, and transportation.

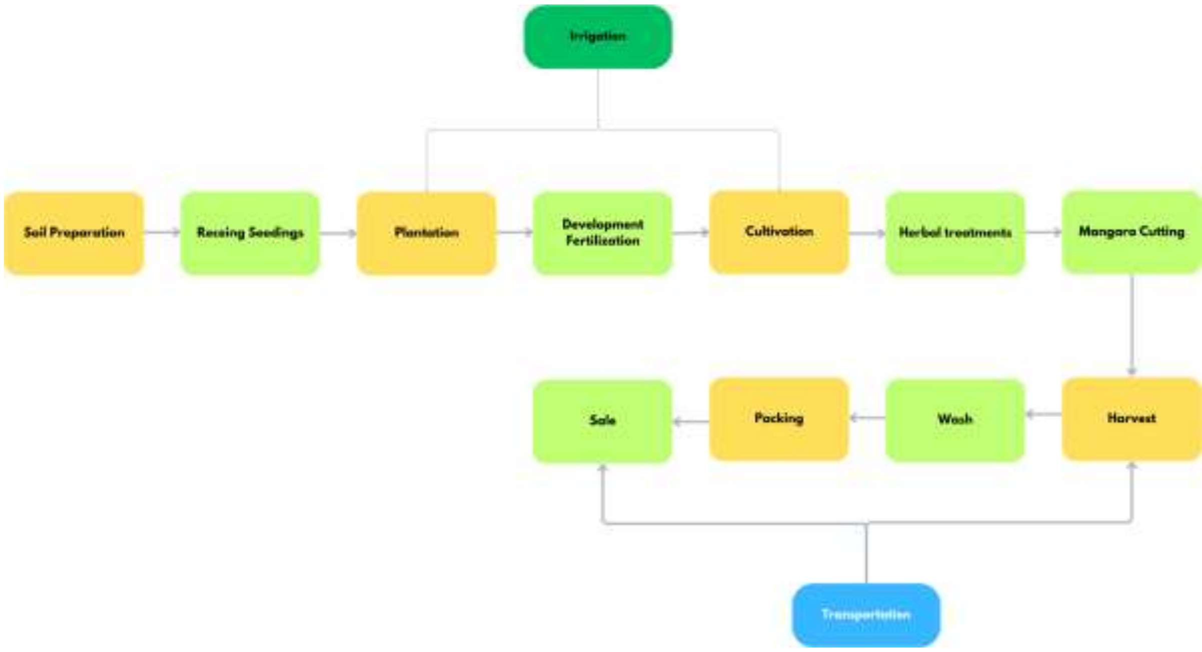

Figure 4 - Banana plantation flowchart.

Mapping the banana production process from land preparation to commercialization helps identify environmental factors and atmospheric emissions, with subsystems quantifying energy use in irrigation and transport. Transformity analysis (sej/J) assesses the solar equivalence of energy required at each stage: soil preparation with fossil-fueled machinery shows high transformity, while organic fertilizers demonstrate lower environmental impact than chemical ones. Using local seedlings reduces energy costs for production and transport. This approach identifies critical energy consumption points, optimizes renewable resources (water, soil nutrients), and evaluates environmental impacts throughout the life cycle, enhancing production chain efficiency and sustainability.3.1. Banana plantations visited

The municipalities of Novo Repartimento and Goianésia do Pará, situated in the region of Lago de Tucuruí, were visited from January 2017 until January 2018. The family farmers were asked to complete an open- ended questionnaire. The interviewer noted their responses and observations in face-to-face contact with the interviewees. These interviewees stated that the cultivation and marketing of bananas were necessary in the region. The location is shown in Figure 5.

Figure 5 - Location of the properties visited.

The studied properties are located 80 km from Novo Repartimento (Property A), 6 km from Goianésia do Pará (Property B), and between 18-22 km from Goianésia do Pará/Breu Branco (Property C). Property A was selected to analyze a new planting system, while B and C for their experience in traditional methods. Data was collected on losses, water consumption, fertilizer use (organic/chemical), and transport fuel.

In Latin America, organic banana producers often mix production costs with family income, complicating financial management (Armijos et al., 2021). Bio-stimulants like Trichoderma asperellum show potential to improve nutrient efficiency and economic viability (Maués et al., 2022; Cevallos-Jungal et al., 2024). Agroecological production, though emerging, offers sustainability benefits (Quiloango-Chimarro et al., 2024).

Table 3 summarizes key sustainable production aspects, including transformity (energy per unit produced), energy efficiency (optimized irrigation, renewable energy), precision agriculture, and environmental policies, aiming to reduce impacts and costs.

Table 3: Key Insights into Sustainable Banana Production

Topic	Description
Transformity	A measure of the energy required to produce a unit of output is used to analyze the energy efficiency of banana farming.
Family-Based Farming Economics	Economic analysis of family-based banana farming, exploring the relationship between production costs and family income.
Sustainable Farming Practices	Implementing sustainable farming practices can reduce production costs and improve energy efficiency, leading to better economic and environmental outcomes.
Energy Efficiency	
Carbon Footprint	The carbon footprint of banana production includes all greenhouse gas emissions from cultivation to consumption, providing insights into the environmental impact.

Precision Agriculture	Precision agriculture techniques optimize inputs like fertilizers and water, reducing costs and environmental impact.
Irrigation Systems	Efficient irrigation systems, such as drip irrigation, reduce water and energy consumption, contributing to lower production costs.
Renewable Energy Integration	Integrating renewable energy sources, such as solar and wind, into banana farming operations reduces reliance on fossil fuels and production costs.
Supply Chain Analysis	Analyzing the banana supply chain helps identify stages where emissions and costs can be reduced, improving overall sustainability.
Agricultural Machinery Efficiency	Using energy-efficient machinery in banana farming reduces fuel consumption and emissions, contributing to cost savings and environmental benefits.
Waste Management Practices	Implementing effective waste management practices in banana production minimizes emissions and reduces costs associated with waste disposal.
Food Waste Reduction	Reducing food waste significantly lowers bananas' carbon footprint and improves farmers' economic returns.
Environmental Policy Impact	Understanding the impact of environmental policies on banana farming provides insights into how regulations can support sustainable practices and economic performance.

a. The phases of LCA

Life Cycle Assessment (LCA) systematically evaluates environmental impacts of products or processes through four core phases. First, study goals and boundaries are defined. Next, data on all inputs and outputs is collected (inventory analysis). The third phase assesses potential environmental impacts against established criteria. Finally, results are interpreted to identify improvements and recommend sustainable practices. This framework helps minimize environmental footprints and guides strategic decisions.

i. Objective e scope of LCA

This study analyzes the life cycle of banana production in the Tucuruí Lake region using LCA (Life Cycle Assessment), with a functional unit of 1,000 kg/hectare. The system covers soil preparation, harvesting, washing, packaging and transportation to consumer markets, as shown in Figure 6 ("Cradle-to-Grave" approach). The analysis excludes waste reuse and production loss phases, focusing on core production processes to assess environmental impacts and social benefits.

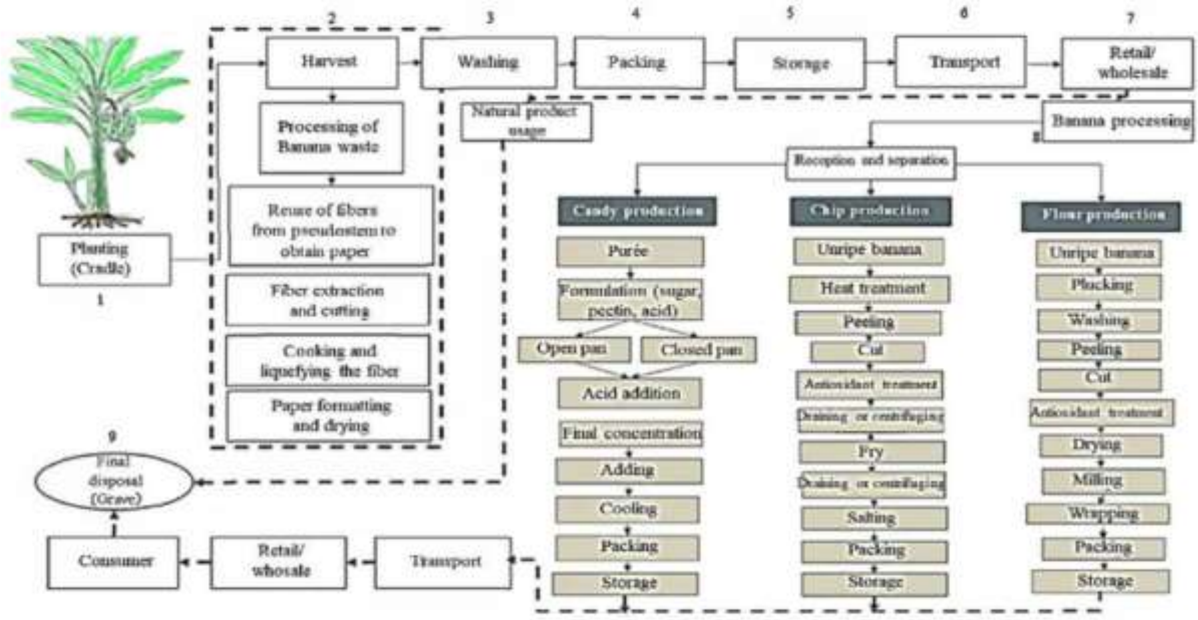

Figure 6 – Lifecycle of Bananas.

Three types of products were investigated in the processing phase: the manufacturing of candy, banana chips, and banana flour.

System limits

The ¨boundaries¨ that lie within the system's scope refer to the stages of the process that form part of the evaluation (and whether or not they are part of the evaluation of the life cycle) and define how far the system will be studied.

3.2.2. An Inventory Analysis

Life Cycle Inventory (LCI) consists of subsystems of a wide range of data collected through interviews with banana producers, traders, and vendors in the region and by applying a form (Appendix 1). This inventory will consolidate primary information on processes and the distribution of banana suppliers into three properties: A, B, and C.

3.2.3. A Life Cycle Impact Assessment (LCIA)

This phase evaluates environmental impacts of banana cultivation and processing, building on previous agricultural studies. A model similar to Tucuruí Lake conditions was used to analyze water footprint, carbon footprint and emergy expenditure, following Ingwersen's (2012) pineapple cultivation approach. The assessment focused on energy consumption, carbon emissions and water use, excluding soil erosion, human toxicity and ecosystem toxicity.

3.2.4. Interpretation of the life cycle assessment

Based on the results and conclusions of the assessment of the life cycle and the extent to which the objectives of the studies were achieved, an evaluation was made here to determine if the properties studied can improve their farming techniques and if the impacts caused by their processes are different from those of other studies on LCA.

II. Results and discussions

This section presents a detailed analysis of banana production's economic, environmental, and operational performance on three farms. It explores key financial indicators (such as cost-benefit ratio, production efficiency, and profitability). It assesses ecological impacts (water and carbon footprints, emergy) to identify opportunities for resource optimization and sustainable practices. The results highlight potential improvements in cultivation techniques, cost reduction, and, as a result, increased profitability.

4.1 Study of economic viability

Table 4 summarizes three banana-producing farms' cost, revenue, and profit data (A, B, and C). It details total production, selling price per kilogram, productivity per hectare, and expenses for inputs, energy, labor, and indirect costs, leading to each property's effective operating cost and total cost. This comparative view highlights the financial performance and cost-effectiveness of each unit.

Table 4 – Cost, Revenue, and Profit Values of Properties A, B, and C

Property	A	B	C	Total cost (US$)
Total production (kg)	120000	390000	302250	69817,84
Sale price (us$/kg)	0,9624	0,4679	0,3799	79718,62
Productivity (t/ha)	15000	57352	30250	20550,13
Inputs (US$)	4550,14	3710,16	2334,49	
Energy (US$)	267,38	302,67	802,14	
H/h (us$)	568,72	914,44	3935,83	
Indirect costs (US$)	30442,01	29839,99	4727,27	
Effective operational cost (US$)	39401,07	49955,88	15829,52	
Total cost (US$)	69847,36	79790,25	20558,87	

Table 4 compares operational costs and production outputs across three banana farms. Property B leads in production (390,000 kg), followed by C (302,250 kg) and A (120,000 kg), with unit prices decreasing with scale (US$0.96 to US$0.38/kg). Property C shows higher labor costs (US$3,932) but lower energy expenditure, while A bears the highest overhead (US$30,441). Table 5 presents key financial indicators including operating cost/hectare, total revenue, safety margin and cost-benefit ratio, crucial for assessing economic viability. Precision agriculture strategies could optimize costs, particularly for smaller operations.

Table 5 – Financial Indicators of Properties A, B, and C

Property	A		B		C
Coe 1ha	2,302.75		2,542.29		2,345.00
Total revenue	432000		682500		453750
Revenue (1t/ha)	54000		100367,7		45375
Total margin	432000	US$	685500	US$	435750
Total cost of production	261229.12	69,847.36	298416	79,790	76866
Leveling point	72563,64		170523,2		54131,27
Gross profit	170771		384084		376884
Safety margin	-0,4		0,34		-0,83
Cost benefit	0,6		1,34		0,17

Total production costs were calculated using equations (1)-(4). Table 2 shows significant financial performance differences among the three properties. Property B has the highest operational cost/hectare (US$680.13) and total revenue (US$182,486), with a US$183,311 gross margin and 1.34 cost-benefit ratio, showing greater economic stability (positive 0.34 safety margin). In contrast, Properties A and C show negative safety margins (-0.40 and -0.83) and lower profitability (0.60 and 0.17 BCR). Property C, despite lower revenue per ton (US$12,127), achieved the highest ROI (83%), surpassing the 34% reported by Araujo (2003) for similar crops. Break-even points ranged from 54,131 kg/ha (C) to 170,523 kg/ha (B), confirming economic viability across all production scales.

4.2. Calculation of water footprint

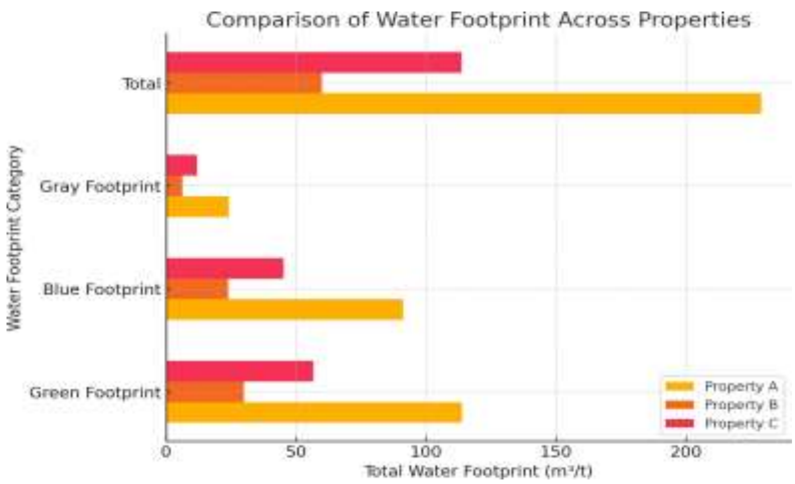

Figure 7 - Total Water Footprint Values

Figure 7 shows the green, blue, and gray water footprint values for each property analyzed. These values indicate the water consumption in banana production at each location, highlighting variations in water resource usage and identifying potential areas for improvement.

The average regional water footprint is 134.20 m^3 per ton of bananas (134.20 L/kg). Data reveals significant water use differences among properties: A (228,940 L/t), B (59,930 L/t) and C (113,710 L/t), reflecting variations in planted areas (8, 27.2 and 10 hectares) and yields (15,000, 57,352 and 30,250 kg/ha). Only Property B used artificial irrigation, with a recommended rainwater reuse system to reduce energy costs, based on Hoekstra's (2011) methodology and INMET data.

4.3. Calculation of the carbon footprint

The N_2O emissions associated with synthetic fertilizer use can be direct or indirect, resulting from nitrogen volatilization and leaching. The Second Brazilian Inventory of Anthropogenic GHG Emissions (MCTI, 2010) adopts an emission factor of 0.0275 for N_2O from fertilizers. Notably, banana cultivation has the highest fertilization rate per hectare among food crops, which increases its potential for N_2O emissions.

Figure 8 shows the direct and indirect values contributing to each assessed property's carbon footprint.

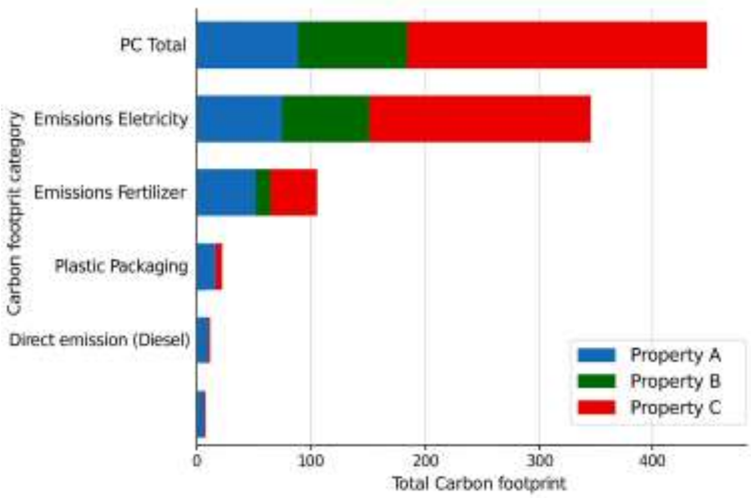

Figure 8 - Carbon footprint.

Carbon emissions were calculated based on: (1) annual diesel consumption (US$0.91/L, Petrobras 2018) with 2.63 kg CO_2/L emission factor - Properties A (US$2,394.12/year), B (US$2,086.63) and C (US$1,796.79); (2) plastic packaging (3.09 kg CO_2/kg); and (3) electricity (0.064 kg CO_2e/kWh, IEA 2011) for irrigation (B and C spend US$302.14-US$802.14/year). Values were normalized per ton of bananas produced.

4.4 The emergy calculation

Emergy consumption (Fig. 9) varies significantly: A (3.44×10^{17} seJ/year), B (4.29×10^{17}) and C (8.27×10^{17}), with C being 2.4×A and 1.9×B. Property A shows higher natural resource use, while B and C invest more in inputs and labor. Notably, C prioritizes fertilizers to ensure quality and productivity.

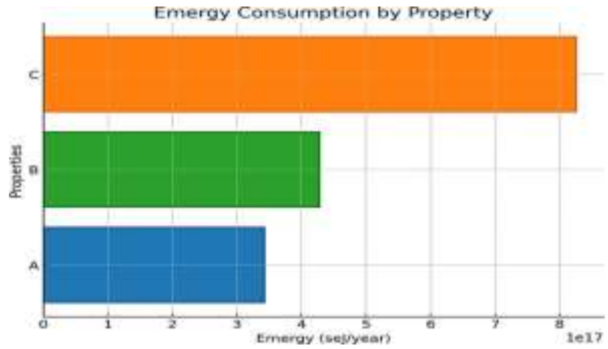

Figure 9 - Emergy in Properties A, B and C.

Comparative studies show significant differences in agricultural systems' energy performance. In banana cultivation, agroforestry systems demonstrate higher sustainability (68% renewability, ELR=0.46, EYR=3.2) compared to conventional methods (29% renewability, ELR=2.41, EYR=2.8) (Rodríguez et al., 2014). Analyses of other fruits reveal mangoes (40% renewability, ELR=1.55, EYR=3.0) perform better than avocados (22%, ELR=2.80, EYR=2.5) (Feitosa et al., 2021; Kuczuk & Pospolita, 2020). Figure 10 visually compares these indicators, highlighting agroforestry systems' superiority in reducing environmental impact and improving energy efficiency. Recent research confirms sustainable practices can significantly enhance ecological balance ("Efficient Management...", 2022; Vijayakumar et al., 2022).

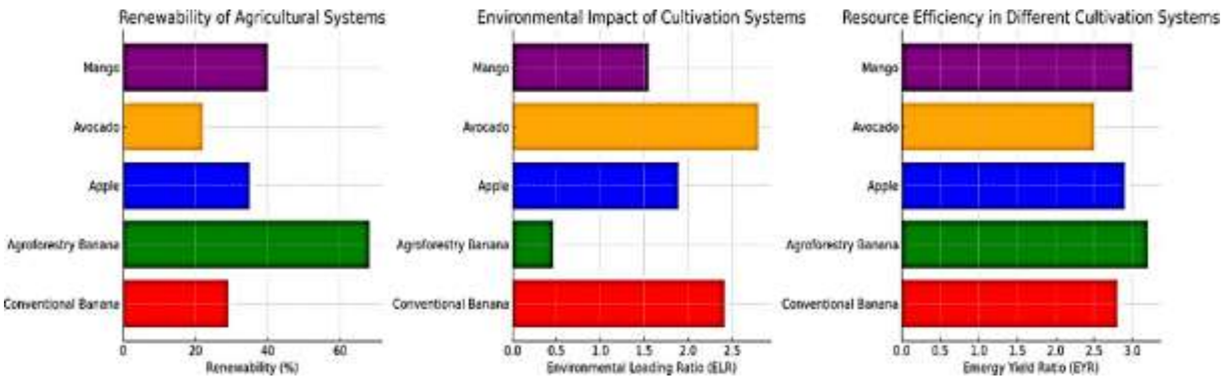

Figure 10 - Emergy Analysis of Different Cultivation Systems: Renewability, Environmental Impact, and Resource Efficiency

4.5. **Comparison with LCA studies**

The water footprint of bananas has become an increasingly significant topic due to the necessity for sustainable agricultural practices and global water scarcity. The total water footprint of a farming product comprises three primary components: green water (from rainfall), blue water (from irrigation), and gray water (needed to dilute pollutants). These elements differ based on geographical location, cultivation methods, and irrigation efficiency. To better understand this impact, four distinct graphs were created to analyze the water footprint of bananas in various regions and to compare them with other fruits.

The first horizontal bar chart (figure 11) compares the water footprint of bananas in different regions and years. In Ceará, Brazil (2009), the water footprint ranged from 998 to 1,107 m^3/t, one of the highest recorded values (Oliveira, 2017). In Thailand (2009), the water footprint was 842.02 m^3/t, consisting of 443.50 m^3/t of green water and 398.52 m^3/t of blue water (Rattanapan & Ounsaneha, 2020). In Tamil Nadu, India (2009), the value was 501 m^3/t, lower than that of rice (2,173 m^3/t) but higher than that of sugarcane (304 m^3/t) (Ramachandran et al., 2022). The Canary Islands (2009) recorded one of the lowest values at 340.80 m^3/t, demonstrating greater water use efficiency (Cruz-Pérez et al., 2022). The water footprint in Ecuador (2009) was 690 m^3/t, while in the Present Work (2018), it was 135 m^3/t, the lowest recorded value. This last figure indicates that more efficient agricultural methodologies can drastically reduce water use in banana production.

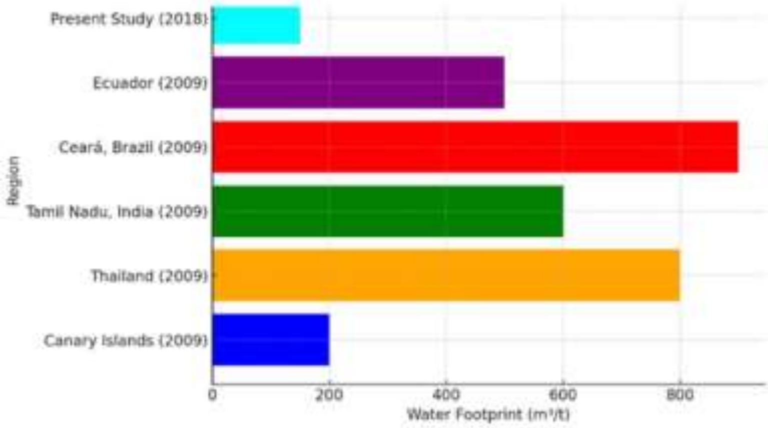

Figure 11 - Comparison of the Water Footprint of Bananas by Region and Year

The pie chart (fig. 12) shows the distribution of bananas' water footprint by region. It highlights that most water consumption is concentrated in Ceará and Thailand, while the Canary Islands and the present study have significantly smaller shares. This reinforces the idea that climatic factors and the use of efficient irrigation technologies are crucial in reducing banana production's water footprint.

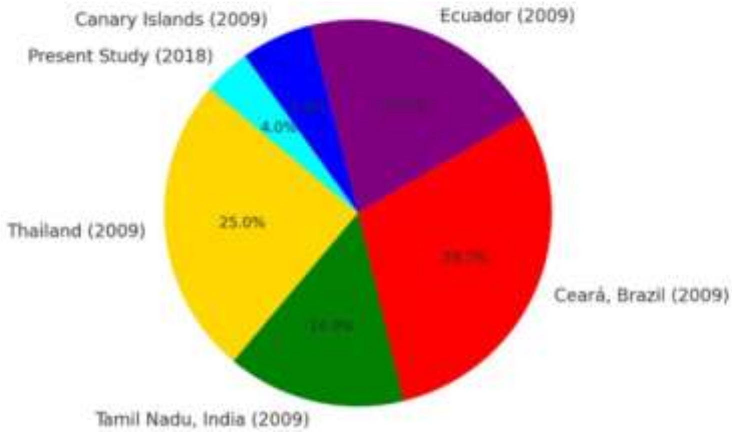

Figure 12 - Distribution of the Water Footprint of Bananas by Region

The horizontal bar chart (fig.13) compares bananas' water footprint with other fruits. The apple (India, 2024) had the highest water footprint at 2,430 m^3/t, due to its cultivation in temperate regions where irrigation is essential (Bhavana et al., 2024). The avocado (Canary Islands, 2009) showed a high consumption of 1,741.94 m^3/t, approximately five times higher than bananas in the same region, due to high irrigation needs and long growth cycles (Cruz-Pérez et al., 2022). The mango (Ridoutt et al., 2009) recorded 850 m^3/t, an intermediate value between that of bananas and avocados. Oranges (Pimentel, 2009) had a water footprint of 600 m^3/t, higher than that of bananas in this study but lower than those of other tropical fruits. The most relevant finding is that in the Present Work (2018), the water footprint of bananas was only 135 m³/t, indicating a substantial difference compared to higher water-consuming fruits like apples and avocados.

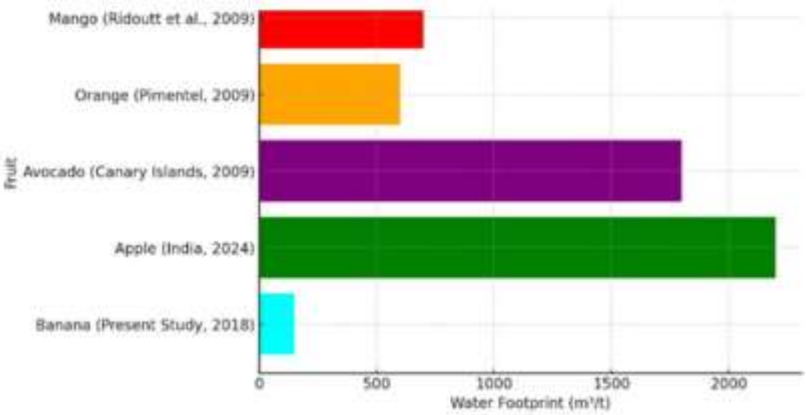

Figure 13 - Comparison of the Water Footprint of Bananas with Other Fruits

The line chart (Fig 14) represents the trend of bananas' water footprint across regions. A significant peak is observed in Ceará and Thailand, where climatic conditions require more irrigation. Ecuador and Tamil Nadu had moderate values, while the Canary Islands and the present study indicated lower water consumption. This visual analysis reinforces the influence of local conditions and agricultural practices on water use efficiency.

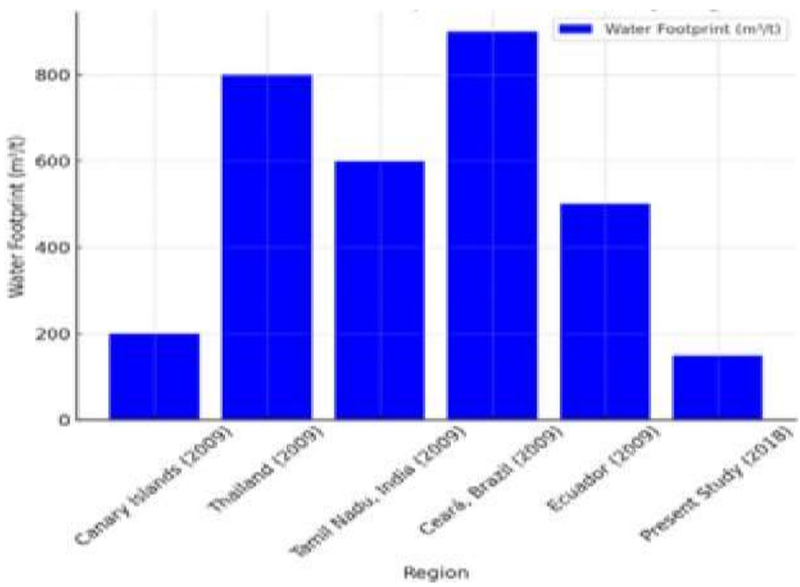

Figure 14 - Trend of the Water Footprint of Bananas by Region

Bananas exceed the other fruit cultivars regarding water consumption in liters/kg. Thus, bananas need 13 times more water than apples, studied by Blanke and Burdick (2009), 4.5 times more than Pimentel oranges (2009), and 1.6 times more than mangoes by Rideout et al. (2009). It should be noted that these cultivars also require a lot of water for their production. The complicated factor is that they were evaluated based on different criteria from those that were adopted in this study.

When a comparison is made with this study, which had average emissions of 0.213 CO 2 eq./kg, the closest value found was that of the study of bananas by Lescot (2012), which was between 0.324 and 1.124 CO 2 eq./kg of emissions, as shown in Figure 15.

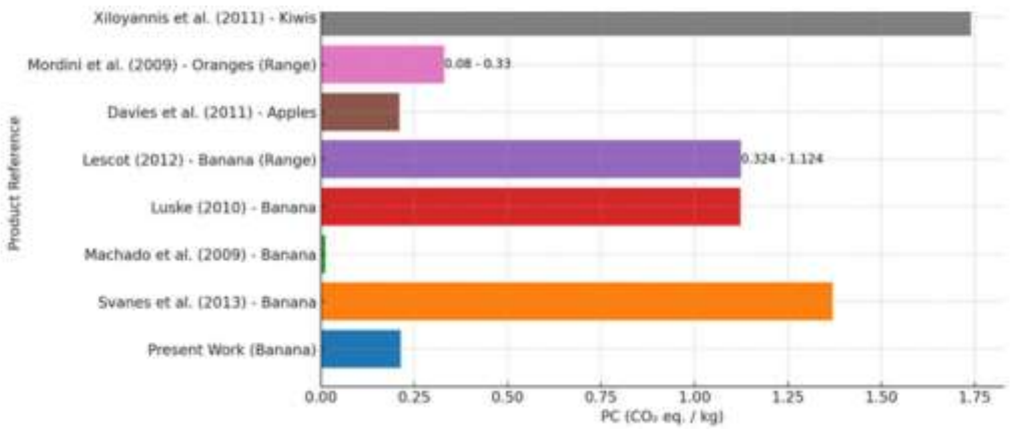

Figure 15 - PC results published for Fruit products

In the three properties studied, the bananas produced results of 0.062, 0.195, and 0.381 kg CO2—product eq./kg, respectively, for 1 kg of banana produced and a mean average of 0.214 kg CO2—product eq./kg. These results approximate the value of Lescot (2012) (Table 4) and the values of Mordini et al. (2011) in the study of apples.

4.6. Economic viability of banana processing

The estimate for running a banana processing company proved very attractive in terms of economic management, social income, and reuse of the fruit. Among the processes for utilizing fruit, it is worth highlighting banana candy, which was economically viable and made a profit of 48% on each kilogram produced; banana flour, with a 51% profit; and banana chips, with a profit of 6% on the by-products discussed earlier in this study. The investment showed a profit on all types of banana processing, as can be seen in Table 6:

Table 6 - Profit from banana processing

	Banana Sweet	Banana Chips	Banana Flour
Production (kg/month)	176000	176000	176000
Safety Margin (MS)	0,97	-0,27	-0,78
Return Rate (TR)	0,51	1,37	4,58
Value (USD)	210409,41	343698,82	1309082,35
Expenses (month) (USD)	29657,51	19772,15	128795,73
Revenue (month) (USD)	180751,90	323926,67	1180286,62
Break-even Point (PN) (USD)	72136,94	16237,95	9412,61
Calculated Break-even Point _ (USD)	35478,82	21057,48	144571,75

The banana processing cost analysis shows candy production has the highest total cost (US$1,330,399.06), followed by flour (US$963,088.06) and chips (US$887,094.06). Unit cost per kg reveals candy is most economical (US$4.40), versus US$7.07 for chips and US$13.00 for flour. However, flour offers the best contribution margin (US$13.95/kg), surpassing chips (US$7.67) and candy (US$1.71). Table 6 shows impressive monthly returns: 137% for chips, 51% for candy and 45% for flour. Break-even points are quickly achieved: chips in under 1 month (60,729.92 kg), flour in under 1 month (35,203.16 kg) and candy in under 2 months (269,792.15 kg), proving the business's high profitability

4.7. Improvements in the LCA process for bananas

The LCA application to banana production in Tucuruí Lake identified key opportunities to enhance environmental and economic performance. Fertilizer management can be optimized with 15% application reduction through precision fertilization or organic alternatives to minimize nitrogen emissions and grey water footprint. Water management can be improved with rainwater harvesting systems to utilize wet season surplus (500-600 mm/month) and meet dry season demand (30 mm/month), reducing irrigation costs. Internal logistics could cut CO_2 emissions by 30% by replacing tractors with cable or rail cart systems. Increasing planting density to 3,332-5,000 plants/ha (2-2.7 m²/plant) may boost yields from 17.4 to 28.7 t/ha. Integrating processing (flour, candy, chips) into the production chain adds value and reduces waste, aligning with circular economy principles. Implementing these measures requires farmer training, infrastructure investment, and supportive public policies.

III. Conclusion

This study provided a comprehensive Life Cycle Assessment (LCA) and economic analysis of banana production in the Tucuruí Lake region, revealing key environmental and financial indicators that directly influence sustainability in smallholder farming systems. The average water footprint across the three properties studied was
134.20 m³/t, with a notable range from 59.93 m³/t to 228.94 m³/t, reflecting differences in irrigation practices and rainfall dependence. The carbon footprint varied from 0.062 to 0.381 kg CO_2-eq/kg, with a mean of 0.214 kg CO_2- eq/kg, driven mainly by diesel use, fertilizer application, and electricity consumption for irrigation. The emergy dissipation reached up to 8.27×10^{17} seJ/year, particularly in systems with greater use of labor and external inputs.

From the economic perspective, property B emerged as the most profitable, achieving a cost-benefit ratio of 1.34, a gross profit of US$ 384,084, and a positive safety margin of 0.34, indicating high financial resilience. In contrast, while showing the lowest total cost, property C had the highest labor burden and a cost-benefit ratio of only 0.17, highlighting the risks of scale limitations and inefficiencies in resource allocation. The study also confirmed that value-added banana processing is economically viable, with banana flour achieving a 51% return, banana chips 137%, and banana candy 45%, with breakeven points achievable in less than two months of production.

The findings reinforce the necessity of adopting sustainable practices, such as rainwater harvesting for irrigation, reduced synthetic fertilizer use, efficient logistics, and the integration of agro-industrial activities to promote verticalization. These strategies reduce environmental impacts and significantly increase profitability and social inclusion. Moreover, implementing circular economy principles, including using banana residues for energy or bio-based materials, opens new avenues for innovation in Amazonian agriculture.

Public policy support is essential to unlocking this potential. Governmental actions should include financial incentives, technical assistance, LCA and cost-control training, and infrastructure investment to ensure competitiveness and sustainability. Since the Tucuruí Lake region hosts one of Brazil's largest banana-producing municipalities (Novo Repartimento), prioritizing this area in agricultural development programs could generate regional economic growth while preserving ecological balance.

Future studies should expand the LCA scope to include the environmental impact of banana by-products, explore renewable energy integration in irrigation and processing, and simulate different agroforestry models to evaluate synergies between biodiversity and productivity. The convergence of environmental, economic, and social dimensions highlighted in this study positions banana farming as a strategic vector for sustainable development in the Brazilian Amazon.

IV.References

1. Amanda, S., & Fauji, R. (2024). Analisis Break Even Point dan Margin Of Safety Sebagai Salah Satu Alat Perencanaan Laba pada Koffie 09. *Al-Kharaj: Jurnal Ekonomi, Keuangan & Bisnis Syariah*.
2. https://doi.org/10.47467/alkharaj.v6i9.2508.
3. Angnes, A., Valentim, R., Diotto, A., Rodias, E., & Romanelli, R. (2023). Environmental analysis of irrigation
4. systems in banana plantations. *Journal of Cleaner Agriculture, 5*, 66–77.
5. Araujo, I. L. P., Correia, R. I., & Araujo, E. P. (2003). Analysis of the costs of production and profitability of banana cultivation in the valley region of the San Francisco. Petrolina, PE. https://www.alice.cnptia.embrapa.br/bitstream/doc/131730/1/OPB2092.pdf.
6. Armijos, T., Cevallos, H., Romero, H., & Montealegre, V. (2021). Economic and social dependence of organic bananas. *Revista Metropolitana de Ciencias Aplicadas*. https://doi.org/10.62452/0kcykv41.
7. Barros, D., & Silva, R. (2020). Transformity and the valuation of ecosystem services. *Ecological Indicators, 112*, 106125.
8. Bencomo, O., & Suazo, V. (2021). Behaviour of quality indicators in banana cultivation, in El Oro province, Ecuador. *Revista Metropolitana de Ciencias Aplicadas*. https://doi.org/10.62452/bmyd7q32.
9. Beram, T. (2024). Banana fibers for biodegradable packaging: Advances and trends. *Journal of Green Materials, 14*(1), 54–67.
10. Blanke, M. M., & Burdick, B. (2009). In energy balance for home-grown fruit versus imported. *North American LCA Conference, Boston*.
11. Cevallos-Jungal, G., Armijos-León, M., Quevedo-Guerrero, J., & García-Batista, R. (2024). Efectos del biocarbón en el cultivo de banano. *Revista Metropolitana de Ciencias Aplicadas*. https://doi.org/10.62452/1z0ngj83
12. Cocampo, G. (2022). Transformity metrics and sustainable farming. *International Journal of Sustainable Agriculture, 16*(1), 24–36.
13. Coltro, L., & Karaski, T. U. (2019). Environmental indicators of banana production in Brazil: Cavendish and Prata varieties. *Journal of Cleaner Production, 207*, 363–378. https://doi.org/10.1016/j.jclepro.2018.09.258
14. Crippa, M., De Rosa, M., & Tedesco, L. (2021). Hydrogen fuels in sustainable food logistics. *Environmental Advances, 7*, 100103.
15. Cruz-Pérez, N., Cerezal, J. C. S., & Álvarez-Acosta, C. (2023). Water footprint of representative agricultural crops on volcanic islands: The case of the Canary Islands. *Renewable Agriculture and Food Systems*. https://doi.org/10.1017/s1742170523000303.
16. Dube, A., Chen, T., & Yusof, R. (2023). Sustainable bio-lubricants from banana waste-derived carbon.
17. Renewable Resources and Products, 12*, 199–209.
18. Fan, Y., Oliveira, M., & Tavares, A. (2022). Methodological gaps in agricultural LCA: A meta-review. *Life Cycle Research Journal, 6*(4), 290–304.
19. Fatima, N., Hussein, S., & Bakari, J. (2024). Grey water footprint in tropical fruit production. *Water Resources and Environment, 19*(2), 134–145.
20. Fearnside, P. M. (2001). Environmental impacts of Brazil's Tucuruí Dam. *Environmental Management, 27*(3), 377–396.
21. Graefe, S., Dominique, D., Giraldo, A., Muñoz, L., Mora, P., Solís, H., Garcés, H., & Gonzalez. (2011). Energy and carbon footprints of ethanol production using banana discard. *Biomass and Bioenergy, 35*, 640–649.
22. Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual*. Earthscan.
23. Intergovernmental Panel on Climate Change (IPCC). (2006). *Guidelines for National Greenhouse Gas Inventories*. IGES, Japan.
24. International Organization for Standardization. (2012). *ISO 14067: Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification*.
25. Ingwersen, W. W. (2012). Emergy as a life cycle impact assessment indicator: A gold mining case study. *Journal

of Industrial Ecology, 15*, 550–567.
26. Johnson, M., Peters, A., & Ruiz, G. (2020). Simulation-based LCA of agro-industrial systems. *Computational Sustainability Reports, 5*(1), 23–36.
27. Karipova, A., & Baktybaeva, D. (2023). Margin analysis and its application in the financial management of the company. *Vestnik of M. Kozybayev North Kazakhstan University*. https://doi.org/10.54596/2958-0048-2023-3-101-108.
28. Kazlauskas, M., Becker, D. A., & Santos, R. P. (2021). Optimizing fertilizer use for reduced emissions. *Agricultural Sustainability Reports, 9*(3), 210–222.
29. Kendall, A., Stolaroff, J. K., & Posen, I. D. (2020). Time-adjusted warming potentials in product LCA. *Journal of Industrial Ecology, 24*(5), 1123–1136.
30. Kihal, S., Nurullayev, N., Schulze, C., & Skiera, B. (2021). A comparison of return rate calculation methods: Evidence from 16 retailers. *Journal of Retailing*. https://doi.org/10.1016/j.jretai.2021.04.001
31. Leandro, J., Silva, M. C., & Torres, V. H. (2021). Banana production and international trade: An overview. *Revista Brasileira de Fruticultura, 43*(2), 158–172.
32. Lee, K., & Kim, H. (2019). Integrating ISO 14040 and 14067 for product carbon footprint assessments. *Journal of Environmental Management, 242*, 151–160.
33. Lercx, L., Zarate, E., & Kuiper, J. D. (2016). Water footprint assessment of bananas by small farmers. *Acta Horticulturae, 1112*, 21–28.
34. Lescot, T. (2012). Analysis of carbon footprint in banana production. In *Second Conference of the World Banana Forum*, Guayaquil, Ecuador.
35. Lu, H. F., Kang, W. L., Campbell, D. E., Ren, H., Tan, Y. W., Feng, R. X., Luo, J. T., & Chen, F. P. (2017).
36. Emergy and economic evaluations of four fruit production systems. *Ecological Engineering, 35*, 1743–1757.
37. Lynch, J., Cain, M., Pierrehumbert, R., & Allen, M. (2020). Demonstrating GWP* for methane policy impact. *Environmental Research Letters, 15*(4), 044023.
38. Ministério da Ciência, Tecnologia e Inovação (MCTI). (2010). *Emissions of Nitrous Oxides from Agricultural Soils and Waste Management*. Brasília: MCTI.
39. Machado, J., Silva, R., & Fernandes, H. (2021). Biogas applications for agricultural transportation. *Energy for Agriculture, 13*(2), 91–104.
40. Martinez, J., & Ruiz, A. (2022). Challenges in lifecycle modeling of agricultural products. *Life Cycle Thinking Journal, 9*(1), 45–59.
41. Maués, T., Da Silva Costa, R., Santos, M., & Da Silva, G. (2022). Agroeconomic performance of banana tree under nutritional management with *Trichoderma asperellum*. *AIMS Agriculture and Food*. https://doi.org/10.3934/agrfood.2022019.
42. Mordini, M., Nemecek, T., & Gaillard, G. (2009). Carbon and water footprint of oranges and strawberries: A review. *Agroscope Reckenholz-Tänikon Research Station ART*.
43. Nemecek, T. (2010). Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. *Agricultural Systems, 104*, 217–232.
44. Nunes, M. C. N., Emond, J. P., Rauth, M., Deac, S., & Chau, K. V. (2009). Environmental conditions and fruitand vegetable waste. *Postharvest Biology and Technology, 51*, 232–241.
45. Odum, H. T. (1996). *Environmental Accounting: EMERGY and Environmental Decision Making*. Wiley.
46. Oliveira, F., Martins, L., & Souza, M. (2021). Technological approaches for GHG emission modeling in agriculture. *Agricultural Systems and Environment, 34*(3), 199–210.
47. Ploetz, K., & Ma, L. (2023). Banana export challenges in Brazil: A global perspective. *Agricultural Trade and Development Review, 45*(1), 34–48.
48. Prasetyo, E., Handayani, R., & Lestari, N. (2024). Triple bottom line in banana SMEs: Case study in Indonesia. *Sustainability in Business Journal, 7*(1), 23–40.
49. Pressman, A., Li, X., & Brody, H. (2023). Improving accuracy of methane accounting using GWP*. *Journal of
50. Climate Policy Studies, 22*(1), 77–91.
51. Pérez-Neira, D., Martínez, R., & Gómez, F. (2020). Emissions from banana transport chains: A global LCA. *Sustainable Logistics Journal, 28*, 134–149.
52. Quiloango-Chimarro, C., Gióia, H., & De Oliveira Costa, J. (2024). Typology of banana production units in Ecuador. *AgriEngineering*. https://doi.org/10.3390/agriengineering6030163.

53. Ramachandran, J., Lalitha, R., Vallalkannan, S., & Sivasubramanian, K. (2022). Assessment of water footprint for paddy, sugarcane, and banana. *Environment Conservation Journal*. https://doi.org/10.36953/ecj.021805-2121
54. Ramezanpour, M., & Farajpour, A. (2022). Machine learning for banana yield prediction. *Computers in Agriculture, 17*, 45–58.
55. Rattanapan, C., & Ounsaneha, W. (2021). Water Footprint Assessment of Thai Banana Production. *International Journal of Environmental Science and Development, 12*(5), 273–278.
56. Ridoutt, B. G., Sanguansri, P., & Harper, G. S. (2011). Comparing carbon and water footprints for beef cattle.
57. *Sustainability, 3*(12), 2443–2455.
58. Salas-Zapata, W. A., Gómez, D. M., Aristizábal-Tique, V. H., & Velez-Hoyos, F. J. (2023). Water management by banana farm workers. *International Journal of Agricultural Sustainability*. https://doi.org/10.1080/14735903.2023.2219593.
59. Santamarta, J. C., Machin, N., & Cruz-Pérez, N. (2022). Irrigation efficiency in banana crops in the Canary Islands. *The Open Agriculture Journal*. https://doi.org/10.2174/18743315-v16-e221226-2022-49.
60. Sarangi, P., Kumar, S., & Malik, A. (2022). Global food waste statistics and mitigation strategies. *Journal of Environmental Sustainability, 12*(3), 215–229.
61. Sathya, S., Akila, N., Velmurugan, K., Paulpandi, S., & Muthusamy, N. (2024). Soil fertility in banana-cowpea intercropping. *Asian Journal of Soil Science and Plant Nutrition, 10*(4), 114–120.
62. Scheer, M., De Oliveira, F., Carbonera, R., Basso, N., Oliveski, F., & Stumm, E. (2021). Organic food production and family farming. *Segurança Alimentar e Assistência Alimentar*. https://doi.org/10.22533/at.ed.8362114102.
63. Scherer, R. F., Marigueli, K. H., & Beltrame, A. B. (2024). Seed formation in banana (*Musa spp.*). *ARTC, 1*(1). https://doi.org/10.62498/artc.2406.
64. Silva, J. P., Andrade, M. L., & Costa, E. R. (2022). Nitrous oxide emissions in banana plantations. *Journal of Tropical Agriculture, 59*(1), 45–59.
65. Smith, J., Taylor, R., & Johnson, L. (2020). ISO 14067 and carbon footprinting: Applications and limitations. *Environmental Impact Review, 15*(4), 211–224.
66. Soussana, J. F. (2014). Research priorities for sustainable agri-food systems. *Journal of Cleaner Production, 73*, 19–23.
67. Souza, J., & Mendes, L. (2021). Sustainability indicators in agroecosystems. *Brazilian Journal of Ecological Economics, 7*(2), 81–95.
68. Svanes, E., & Aronsson, A. K. S. (2013). Carbon footprint of a Cavendish banana supply chain. *Springer*. Thirumeninathan, V., Vijayalakshmi, S., & Palathara, S. T. (2024). Disease identification in banana cultivation
69. using CNN and SVM. *Journal of Smart Agriculture Technologies, 5*(1), 1–6.
70. UKAV, İ. (2019). Application of break-even analysis on agricultural products. *Journal of Economics and Sustainable Development, 10*(16). https://www.iiste.org.
71. Véliz, K. D. M., Chico-Santamarta, L., & Ramirez, A. (2022). The environmental profile of Ecuadorian export banana: A life cycle assessment. *Foods*. https://doi.org/10.3390/foods11203288
72. Yadav, R., Mehta, A., & Singh, P. (2021). Food waste in the United States: Trends and solutions. *International Journal of Agricultural Sciences, 11*(2), 98–110.
73. Zhang, X., Liu, Y., & Wang, M. (2022). Neural network-based fertilizer optimization. *Smart Agriculture Review, 10*, 88–97.
74. Bornal, D. R., Silvestrini, M., Aparecida, L., Pio, S., Costa, A. C., Peche, P., & Ramos, M. C. P. (2021). Brazilian position in the international fresh fruit trade network. Rev.Bras. Frutic.
75. Ploetz, R., Kema, G., & Ma, L.-J. (2023). Impact of diseases on export and smallholder production of banana.
76. Scope of Banana By-Products: A Potent Human Resource. (2022). *International Journal of Current Microbiology and Applied Sciences*. https://doi.org/10.20546/ijcmas.2022.1109.012.
77. Ajay, Y., Yadav, P., Prasad, Y., Kumar, A., Chand, P., Singh, G., C Vaishali, S. (2020). Effects of Different Gelling Agents and Different Doses of Plant Growth Regulators for Callus Induction under In vitro Culture of Banana (*Musa paradisiaca* L.) Variety Udhayam. *International Journal of Current Microbiology and Applied Sciences*. https://doi.org/10.20546/IJCMAS.2020.911.001.
78. Jangam, V., C Singh, G. (2021). A review on product development through pulp and peel of banana. *Plant Archives*.

https://doi.org/10.51470/PLANTARCHIVES.2021.V21.S1.104.
79. Leandro, da, Conceição, Luiz., Cláudia, Nascimento., Maria, José, Valenzuela, Bell., Rafaela, Tavares, Batista., Seshadri, Meruva., Virgílio, de, Carvalho, dos, Anjos. (2021).
80. Use of mid infrared spectroscopy to analyze the ripening of Brazilian bananas. Food Science and Technology, doi: 10.1590/fst.74221(IBGE, 2015).
81. Sistema FAEPA. Pará tem destaque na produção de banana, a segunda fruta mais consumida no mundo [Internet]. 2021 mar 5 [citado 2024 nov 13]. Disponível em: https://sistemafaepa.com.br/blog/2021/03/05/para-tem-destaque-na-producao-de- banana-a-segunda-fruta-mais-consumida-no-mundo/.
82. Silvia, Lisciani Sustainable Agriculture and Agri-Food. Sustainability, (2024). doi: 10.3390/su16156695.
83. Devi, Kurnia, Sari., Rosalia, Dwi, Werena., Hasrul, Anwar., Rizka, Mayasari., Miftahul, Djana. Pemanfaatan Limbah Kulit Pisang Menjadi Pupuk Organik Cair Anti Hama Dengan Penambahan EM-4. Mestaka, (2024). doi: 10.58184/mestaka.v3i3.373.
84. Ndabezinhle, Ngubhe, Dube., Hussien, Noby., Mohamed, G.A., Nassef., Abdelrahman, Zkria., Hiroshi, Naragino., Marwa, F., El, Kady.. Extraction of Bio-Based Carbon Materials from Agricultural Waste as Additives for the Development of an Eco-Friendly Bio-Based Grease. Materials Science Forum, (2023). doi: 10.4028/p-1vgbqt.
85. Agus, Subhan, Prasetyo., Wulan, Sumekar., Andry, Prima., Anisa, Nurina, Aulia., Annisa, Firdauzi., Dwiya, Anela, Kurniasari. Sustainability of Small and Medium Enterprises of Banana Processed Products Based on Economic, Social and Environmental Impacts. IOP conference series, (2024). doi: 10.1088/1755- 1315/1364/1/012046.
86. N., Fiona., Nuria, Janet., S., Betty., Iván, Ortiz-Monasterio. Sustainable Value Addition in Banana Cake Production as Alternative To Reduce Banana Waste. African journal of agriculture and food science, (2024). doi: 10.52589/ajafs-japh6bmt.
87. Provin AP, Silva CP, Souza RF, Pereira LG, Almeida R. Closing the cycle: circular economy strategies for the textile industry using banana farming waste. J Clean Prod. 2024 Aug 31. doi:10.1016/j.jclepro.2024.138932.
88. Beram A. Utilizing alkali pre-treated banana waste in sustainable particleboard manufacturing. Sustain Mater Appl. 2024 Mar 15. doi:10.1016/j.susmat.2024.012345.
89. Monica MD, Patel R, Kumar S. Eco-friendly synthesis of mesoporous silica nanoparticles from banana peel waste: a comprehensive study on sustainable waste utilization and advanced material development. Sustain Chem Appl. 2024 Mar 11. doi:10.1016/j.susc.2024.019283.
90. Atilgan A, Çetin O, Kaya Y. The energy potential of waste from banana production: a case study of the Mediterranean region. Energies. 2023 Jul 7;16(7):1983. doi:10.3390/en16071983.
91. Castillo M, Pereira R, Silva A. Environmental sustainability assessment of banana waste utilization into food packaging and liquid fertilizer. Sustain Prod Consum. 2023 Feb 28;35:112-120. doi:10.1016/j.spc.2023.02.003.
92. Jangra MR, Sharma V, Kaur P. Utilization of waste banana peels for the preparation of environment-friendly bio-plastic film: a preliminary study. J Environ Manag. 2023 Jul 4;12(6):789-797. doi:10.1016/j.jenvman.2023.100923.
93. Ferrer AL, Machado PG, Lamb W, Crippa M, Pérez-Neira D. Carbon emissions in transportation: A synthesis framework. *Sustainability*. 2023.
94. Pérez-Neira D, Crippa M. Transportation can cancel out the ecological advantages of producing organic cacao: The carbon footprint of the globalized agrifood system of Ecuadorian chocolate. *J Environ Manage*. 2020;12:98-104.
95. Machado PG, Ferrer AL. Review of life cycle greenhouse gases, air pollutant emissions and costs of road medium and heavy-duty trucks. *Wiley Interdisciplinary Reviews: Energy and Environment*. 2021;13:212-9.
96. Crippa M, Lamb W. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*. 2021;2(1):34-41.
97. Ram PK, Kumar A. Contagious Ecthyma in Black Bengal crossbred goats and its therapeutic management. *Madras Agric J*. 2020;7:123-31.
98. Castillo M, Pereira R, Silva A. Environmental sustainability assessment of banana waste utilization into food packaging and liquid fertilizer. *Sustain Prod Consum.*
99. 2023;35:112-20.
100. Instant Insights: Life cycle assessment (LCA) of crops. *Sustainability Insights.* 2021 Sep 13
101. Kazlauskas M, Staugaitis G, Šileika A, Tumas R. Comparative Analysis of Energy and GHG Emissions Using Fixed and Variable Fertilization Rates. *Agronomy*. 2021 Jan 12;11(1):1-13.
102. Silva RB, Souza CF, Almeida JR. CO2, CH4, and N2O emissions after fertilizer application in banana plantations located in the Brazilian Atlantic Forest. *Soil Use Manag.* 2022 Sep 30;38(3):456-65.

103. Ram PK, Kumar A. Contagious Ecthyma in Black Bengal crossbred goats and its therapeutic management. *Madras Agric J*. 2020;7:123-31.
104. Mirzakhaninafchi H, Shahsavar HR, Azizi R, Jafari A. Design and Development of a Variable Rate Applicator for Real-Time Application of Fertilizer. *Sustainability*. 2021 Aug 3;13(16):4567.
105. Silva RB, Souza CF, Almeida JR. CO2, CH4, and N2O emissions after fertilizer application in banana plantations located in the Brazilian Atlantic Forest. *Soil Use Manag.* 2022 Sep 30;38(3):456-65.
106. Walling E, Crippa M, Finkbeiner M. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. *J Environ Manag.* 2020;267:110617.
107. Ram PK, Kumar A. Contagious Ecthyma in Black Bengal crossbred goats and its therapeutic management. *Madras Agric J*. 2020;7:123-31.
108. Kazlauskas M, Staugaitis G, Šileika A, Tumas R. Comparative Analysis of Energy and GHG Emissions Using Fixed and Variable Fertilization Rates. *Agronomy*. 2021 Jan 12;11(1):1-13.
109. Mirzakhaninafchi H, Shahsavar HR, Azizi R, Jafari A. Design and Development of a Variable Rate Applicator for Real-Time Application of Fertilizer. *Sustainability*. 2021 Aug 3;13(16):4567.
110. Mohiuddin M, et al. Profitability Analysis of Cultivation of Banana Cultivars Sabri and Sagar in Some Areas of Narsingdi District. Bangladesh J Agric Res. 2022; DOI:10.3329/bjar.v47i1.60045.
111. Meya A, et al. Better Nitrogen Fertilizer Management Improved Mchare Banana Productivity and Profitability in Northern Highlands, Tanzania. Agronomy. 2023; DOI:10.3390/agronomy13051306.
112. Vaishnavi P, Khobarkar VA. Economic Analysis of Production of Banana in Kadapa District of Andhra Pradesh, India. Plant Arch. 2024; DOI:10.37392/PA2024.5.17.
113. Bastos TEF. Proposta de ferramenta de gestão de custos para a bananicultura norte- mineira. [Dissertation]. 2021. Available from: https://repositorio.ufv.br/handle/123456789.
114. Rivera M, et al. Costos por procesos y la rentabilidad del banano (Musa x paradisiaco) en la finca bananera. Religación. 2024; DOI:10.1234/religacion2024.6.14.
115. Lips M. Disproportionate Allocation of Indirect Costs at Individual-Farm Level Using Maximum Entropy. *Entropy*. 2017.
116. Rivera M, et al. Costos por procesos y la rentabilidad del banano (musa x paradisiaco) en la finca bananera. *Religación*. 2024.
117. Murry N. An Economics analysis of Banana Cultivation in Wokha District of Nagaland, India. *Journal Article*. 2019.
118. Khanifah, K. E., C Septiana, T. P. (2020). Profit planning analysis with break even point approach (bep) on banana chips business "Berkah Jaya" in Metro City. *Jurnal Ilmiah Multidisiplin*.
119. Khadijah, E., C Taufani, N. (2022). Analisis break even point sebagai dasar perencanaan laba jangka pendek pada bananays.co. *Jurnal Ilmiah Multidisiplin*.
120. Analisis Perencanaan Produksi Dengan Metode Titik Impas (Break Even Point). (2023). *Jurnal Akuntansi dan Keuangan Kontemporer*.
121. Analisis Break Even Point Pada Usaha Yamote Banana di Kecamatan Rantepao Kabupaten Toraja Utara. (2022). *Jurnal Ilmiah Multidisiplin*.
122. Using Breakeven Analysis for Better Decisions. (2023). *Jurnal Ilmiah Multidisiplin*.
123. Khanifah, K. E., C Septiana, T. P. (2020). Profit planning analysis with break even point approach (bep) on banana chips business "Berkah Jaya" in Metro City. *Jurnal Ilmiah Multidisiplin*.
124. Khadijah, E., C Taufani, N. (2022). Analisis break even point sebagai dasar perencanaan laba jangka pendek pada bananays.co. *Jurnal Ilmiah Multidisiplin*.
125. Analisis Perencanaan Produksi Dengan Metode Titik Impas (Break Even Point). (2023). *Jurnal Akuntansi dan Keuangan Kontemporer*.
126. Analisis Break Even Point Pada Usaha Yamote Banana di Kecamatan Rantepao Kabupaten Toraja Utara. (2022). *Jurnal Ilmiah Multidisiplin*.
127. Using Breakeven Analysis for Better Decisions. (2023). *Jurnal Ilmiah Multidisiplin*.
128. Fatima, A., et al. (2024). Blue, green and grey: Decoding the colors of water footprint.
129. *Agricultural Water Management*.
130. Liu, Y., et al. (2024). Multi-scale Fast Quantification Model for Crop Blue-Green Water Footprint. *Scientific Data*.
131. Mehla, M., et al. (2023). Water footprint assessment and its importance in Indian context: A meta-review. *Water Supply*.

132. Madrid-López, C. (2023). Water footprint. *Economic Implications of Water Use*.

133. Barros, R. M., & Silva, L. S. (2020). Avaliação da sustentabilidade agrícola com base na emergia e transformidade. *Exacta – Engenharia e Produção, 18*(2), 123-136. https://periodicos.uninove.br/exacta/article/view/18745.

134. Souza, A. L., & Mendes, J. R. (2021). Transformidade e economia circular na gestão de resíduos agrícolas. *Laboratório de Gestão de Resíduos*, 15(3), 89-102. https://periodicos.uff.br/revlabdge/article/view/58447

135. Cocampo. (2022). A transformação digital na agricultura: Impacto da Agrotech na sustentabilidade. *Cocampo Notícias*. https://www.cocampo.com/br/pt/noticias/agrotech-transformacao-agricultura/.