OPEN ACCESS

ORIGINAL ARTICLE

Revista Ciencias Técnicas Agropecuarias 35
January-December 2026
ISSN 1010-2760, eISSN 2071-0054
Cu-ID: https://cu-id.com/2177/v35e19

Procedure for Implementing a Minibiofactory of Bioinputs in Circular Biotechnology on Farms in Mayabeque

Procedimiento para implementar una minibiofactoría de bioinsumos en la biotecnología circular en fincas de Mayabeque

Mayra Arteaga Barrueta[1*] and José Antonio Pino Roque[2]

[1]*Universidad Agraria de La Habana, Facultad de Agronomía, Departamento de Química, San José de las Lajas, Mayabeque, Cuba.*
[2]*Universidad Agraria de La Habana, Facultad de Ciencias Técnicas, Departamento de Matemáticas, San José de las Lajas, Mayabeque, Cuba. E-mail: pino@unah.edu.cu*

[*]Autora para correspondencia: Mayra Arteaga Barrueta, e-mail: mayra@unah.edu.cu

ABSTRACT: Agricultural autonomy on farms is a key challenge for local development, mitigating dependence on external inputs, especially in degraded soils with environmental impact. A potential solution involves implementing of a cyclical model that fully utilizes endogenous waste, centered on a mini-biofactory for bio-inputs to transform organic waste into biological inputs of high agronomic value. The objective is to propose a comprehensive, adaptable, and replicable methodology for designing a mini-biofactory that contributes to the autonomy of the Guayabal farm and serves as a model for the Mayabeque region. Methodologies from the literature were validated and adapted to the endogenous conditions of the Guayabal farm for the implementation of a mini-biofactory as an emerging alternative for the sustainable management of waste. These methodologies were adapted to the specific conditions of the Guayabal farm, selected as the study center due to its integration of stakeholders in local production, teaching, research, and training activities. With this design, a self-sufficiency of 162% in obtaining bio-inputs was estimated, along with a return on investment in 16 months and a projected improvement in soil organic matter from 1.55% to 4% over 3 years. These results suggest the feasibility of its implementation and the increase in resilience, making the model a benchmark for cyclical self-sustainability using local resources. These theoretical projections, which require empirical validation in subsequent stages, not only define the pioneering nature of the work but also lay the methodological groundwork for future implementations of mini-biofactories in the region.
Keywords: Agroecology, Sustainability, Nutrient Cycling, Waste Recycling.

RESUMEN: La autonomía agrícola de las fincas constituye un reto clave en el desarrollo local para mitigar la dependencia de insumos externos, especialmente en suelos degradados y con impacto ambiental. Una solución alternativa es la implementación de un modelo cíclico que aproveche integralmente los residuos endógenos, centrado en una minibiofactoría de bioinsumos para transformar desechos orgánicos en insumos biológicos de alto valor agronómico. El objetivo es proponer una metodología integral, adaptable y replicable para diseñar una minibiofactoría que contribuya a la autonomía de la finca Guayabal y sirva de modelo para la localidad de Mayabeque. Se validaron y adecuaron metodologías de la literatura a las condiciones endógenas de la finca Guayabal para la implementación de una minibiofactoría como alternativa emergente para el manejo sostenible de residuos. Estas se adecuaron a las condiciones endógenas de la finca Guayabal, seleccionada como centro de estudio por su articulación entre actores en actividades productivas, docentes, investigativas y de capacitación local. Con este diseño, se estimó una autosuficiencia en la obtención de bioinsumos del 162%, un retorno de la inversión en 16 meses y una mejora proyectada de la materia orgánica del suelo del 1.55 a 4% en 3 años. Estos resultados sugieren la viabilidad de su implementación y el aumento de la resiliencia, convirtiendo el modelo en un referente de autosostenibilidad cíclica con recursos propios. Estas proyecciones teóricas, que requieren validación empírica en etapas posteriores, no solo definen el carácter pionero del trabajo, sino que también sientan las bases metodológicas para futuras implementaciones de minibiofactorías en el territorio.
Palabras clave: agroecología, sostenibilidad, ciclo de flujos de nutrientes, reciclaje de residuos.

INTRODUCTION

The creation of sustainable models for local farms based on the principles of circular agriculture is a current challenge. These models mimic natural cycles through cyclical practices such as biomass recycling and the use of bio-inputs (Altieri, 2002), seeking to reduce the ecological footprint by conserving and protecting biodiversity, soil, and water (Gliessman, 2018); as well as promoting energy efficiency with renewable resources (FAO, 2018)

Received: 15/11/2025
Accepted: 27/04/2026
Conflict of interests: The authors of this work declare no conflict of interests.
Author Contributions: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing - original draft: Mayra Arteaga. **Supervision:** José Pino. **Formal analysis Writing-review & editing:** Mayra Arteaga. José Pino.
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In Cuba, research on closing nutrient cycles exists in studies with specific, isolated, and mixed approaches. Notable examples include: models in pastures, efficiency under favorable climatic conditions (Funes-Monzote, 2008); and operational biofactories (CREE, local production of compost, bokashi, violets, plant slurries, and Trichoderma fungi); although their distribution and scaling are uneven and not widespread (Rosset *et al.*, 2011). Furthermore, logistical challenges and climatic effects persist, limiting the quality of waste products (Machado *et al.*, 2017), These factors contribute to inconsistencies in the quality of artisanal bio-inputs due to limited infrastructure and the lack of widespread dissemination of cyclical farming practices from farmer to farmer (Fundora *et al.*, 2024).

Nevertheless, this background shows results in soil, crop, and biodiversity improvement, as well as pollution reduction, providing a basis for implementing mini-bio-input biofactories as a cornerstone of circular agriculture in self-managed local farms.

The Guayabal farm, as a teaching-production-research model, constitutes an ideal setting to replicate Cuban successes and minimize shortcomings through the validation and adaptation of the methodology described by Arteaga & Pino (2025), to the specific conditions of local farms. The objective of this work was to propose a comprehensive, adaptable and replicable methodology to design a mini-biofactory that contributes to the autonomy of the Guayabal farm and serves as a model for the locality of Mayabeque.

MATERIALS AND METHODS

General Methodological Design

The work procedure was based on the linking, validation, and adaptation of two methodologies proposed by Arteaga & Pino (2025), for the design and implementation of mini-biofactories for agricultural bio-inputs on local farms, specifically in the Mayabeque province.

A procedure was derived according to the characteristics and endogenous conditions of the Guayabal teaching farm. It was developed with a mixed-methods approach (qualitative-quantitative) and structured as a single case study (Yin, 2014) with elements of participatory action research integrated with the knowledge of local stakeholders at the Guayabal farm, laboratory analysis, and technical-economic modeling.

This protocol was methodologically structured by integrating indicators that would allow for the required multifunctionality, in order to achieve continuous improvement of the integrated endogenous strategic actions to be developed through the most cost-effective and viable pathways for the gradual (phased) implementation and final establishment of Self-Sustaining Circular Mini-Biofactories on farms at the individual or community level, under the local endogenous conditions of the Mayabeque province, applicable to Cuba as a whole, to contribute to food sovereignty and environmental sustainability of the territory.

The general methodological design included three sequential phases: (I) Phase 1. Farm characterization and baseline diagnosis: aimed at understanding the endogenous conditions (physical, chemical, biological, and socio-productive) that influence the implementation of a mini-biofactory. (II) Phase 2. Design of the procedure for the implementation of the mini-biofactory: based on the integration of theoretical frameworks, previous experiences, and participatory tools with local stakeholders. (III) Phase 3. Feasibility Assessments of the Proposal: projections of self-sufficiency, economic return, and soil improvement based on the information generated in the previous phases. This design allowed for the development of a contextualized, replicable procedure grounded in the farm's actual conditions.

Selection of the Study Area

The research was conducted at Finca Guayabal between 2021 and 2025, located in the municipality of San José de las Lajas, Mayabeque Province, Cuba (22° 59′ 55″ N, 82° 01′ 02″ W). The farm was intentionally selected (purposive sampling) due to its high level of collaboration among producers, educators, researchers, and the community, making it a model for local training and replication. This collaboration is manifested in the ongoing partnership with the Agrarian University of Havana (UNAH), the Scientific Complex, and in its participation in agroecological innovation networks, involving producers.

Phase 1: Farm Characterization and Baseline Diagnosis

Climatic Context of the Study Area

Table 1 summarizes the average annual climatic conditions recorded during the study period, from 2021 to 2025, for the Guayabal farm area in San José de las Lajas, Mayabeque, by the Cuban Institute of Meteorology. It highlights trends compiled from historical average data (2010-2024) for the area (INSMET-Cuba, 2025). These constitute independent variables that influence the dynamics of the agroecosystem, the generation of biomass, the production of organic waste and the conservation and transformation processes proposed on the farm over time.

Variables and Parameters Evaluated

Based on the described climatic context, 18 physical-chemical, biological, and socio-productive parameters of the farm were evaluated, as shown in Table 2. The main dependent variables included: (I) soil organic matter content (%), (II) soil pH, (III) nutrient availability (N, P, K), (IV) organic waste generation - kg/month (a variable directly influenced by climatic conditions of temperature and precipitation), (V) agroecosystem management, (VI) composition of the generated waste, and (VII) socio-productive indicators (labor, organization, among others).

Table 1. annual mean climatic data recorded for the area of San josé of the Flagstones, Mayabeque

Parameters annual means	Year 2021 at the 2025	Tendency observed with relationship to the ago 30 year-old historical stocking
Precipitation mm	≈533-650	Decrease of 54-62%
	Marked	Alternation of dry and humid years Dry station (Nov-Abr) Rainy station (May-Oct)
Temperature ^{0}C	24.5-25.5	T.max.+ 1 -2.5 ^{0}C
Relative humidity	70-81%	Smaller in the dry season
Extreme events	drought and hurricanes	Increased in frequencies and intensity

Sampling and Data Collection

A simple random sampling design was established in three main plots of the Guayabal farm (intensive crop area, pastureland, and reserve area). In each plot, 10 single samples were taken at a depth of 0-20 cm using an auger. The single sample from each plot was homogenized to obtain a composite sample per plot (n = 3 composite samples in total).

Sampling was carried out during the dry season (March) to ensure stable moisture conditions. Each sampling point was georeferenced using GPS.

Residue Data Collection

A participatory inventory of organic waste generated on the farm was conducted over 30 consecutive days. The brigade leader and two producers recorded the waste daily on templates designed for the study, which included: (I) type of waste (manure, crop residue, pruning waste, plants, etc.). (II) estimated quantity (kg). (III) Current destination (burning, stockpiling, animal feed, etc.).

Selection of participants for interviews and workshops

Purposive sampling was used to select key stakeholders connected to the farm (Kvale, 2011): (I) Inclusion criteria were based on length of service on the farm (more than 2 years). (II) Participation in production decision-making and willingness to collaborate. (III) The selected participants were 20 key stakeholders (farm management council (3), 2 brigade leaders, 5 permanent stakeholders, and 10 farm and university specialists who support innovation processes on the farm).

Qualitative Data Collection Techniques

The following qualitative data collection techniques were applied with the prior consent of the farm stakeholders:

(I) Semi-structured interviews were conducted using a guide with open-ended questions about: perception of waste, knowledge of bio-inputs, usefulness of waste, impact of its use, willingness to change, and expectations (Kvale, 2011).

(II) Participant observation was carried out through six field visits (February, March, and April 2025) to directly observe waste flows and bio-input needs, using audio recordings, photos, and field notes, with the respective georeferencing. (III) A participatory diagnostic workshop was convened with The focus group technique (Morgan, 1997), was applied to 50% of the selected stakeholders on the farm to identify problems related to waste management and input needs, using audio recordings, photos, field notes, and georeferencing. (IV) Analytical methods from characterization laboratories for soil, bio-inputs, and bromatological studies of organic waste, referred to in Table 2 and carried out in the laboratories of the Faculty of Agronomy of the Agrarian University of Havana (UNAH) and the National Institute of Agricultural Sciences (INCA).

Phase II: Design of the procedure for the implementation of the mini-biofactory

Objective of the design

A theoretical technical-methodological procedure was designed for the physical and operational implementation of a mini-biofactory for bio-inputs on the Guayabal farm. This procedure comprises the set of steps, tools, and conditions necessary to install and operate the system (pilot and scaled-up levels). adapted to the farm's endogenous conditions.

Sources and technical references for the design

A literature review of national and international experiences was conducted, consulting more than 25 publications from the period 2010-2025 in databases such as Scopus and SciELO. National contributions included: the "El Patio" mini-biofactory Reyes *et al.* (2022), integrated community biofactories in Granma (Pérez *et al.*, 2021), and low-cost biodigesters in the provinces of Mayabeque and Havana (González & Martinez, 2019; IS-Cuba, 2023) International references included the implementation of agroecological design principles (Altieri & Nicholls, 2012), González & Martinez, 2019), biofactories, waste management models (Castro & Fernández, 2023), and nutrient cycle closure. (Rodríguez *et al.*, 2020). The analysis of these references allowed for the identification of best practices, limitations, and lessons learned, which were incorporated into the procedure design to adapt it to the specific conditions of the Guayabal farm.

Participatory Tools for Procedure Design

Three participatory workshops were held (June-October 2024) with the same key stakeholders from Phase I for the collaborative development of the procedure. The techniques used are shown in Table 3.

Table 2. Parameters and Methods of characterization of characterization

Parameter	Calculation methodology	Source / calculation Base
Determination of space data of the property with images satellites Images satellites Sentinel was processed-2 (15 September of the 2021-2025), with validation in situ (USGS, 2025)	GPS Sentinel-2 (B4-RED,8-NIR, 10m head.). COPERNICUS OPEN ACCESS HUB QGIS 3.28 I inventory direct and analysis of the NDVI Calculations NDVI + zonal Statistics Temporary analysis NDVI NDVI = (NIR-NET) / (NIR+RED) NIR: Band 8 to GO near NET: Banda4(red) of Sentinel-2 Application of coefficients of use Models (Estimate of the biomass (t/ha) with the NDVI.	Science for Changing wold USGS, Sentinel Hub, 2024 Fernández (2020) Costo *et al.* (2020) Chave *et al.* (2014) González *et al.* (2021) INIVIT-Cuba (2023) FAO (2017; 2018; 2021) Dengsheng *et al.* (2016)
Estimate of the Vegetable Biomass BV (t/ha year), by means of the analysis NDVI and applying direct inventory	BV = Yield cultivation (t/ha) x area index x of use harvests standard Coef.residuo cultivations 0.3-0.5	González *et al.* (2021) Taiz (2025) IPCC (2019) Gofc-gold (2023)
Production of manure PE (t/año), using values standard	PE = N0. Heads x daily half production (kg/d) x 365/1000. Coef. 10kg/d Bovine; 25-30 kg/d Smaller: 2-4 kg/d	FAO (2018; 2021; 2022) López *et al.* (2020) IPCC (2019)
Balance of nutritious (NPK),	Deficit (kg) = (' area has x Extraction half cultivation kg/ha)-(content of nutritious in floor kg/ha)-it contributes bioinputs, using coef. of extraction	INCA-Cuba (2020) FAO (2018; 2021)
Alimentary self-sufficiency (%)	%= (biomass foragers produced property t)/ total Requirement of the livestock t) x 100 Coef. efficiency compostaje 50%	Funes-Monzote, (2008) FAO (2021; 2022)
Floor analysis in samples made up of 0-20 cm of depth Potassium Nitrogen	Analysis of the recycle of nutritious (NPK), comparing the nutrients for cultivation (kg/ha/ year), using requirement chart Extraction of N cultivations 120kg/ha	FAO (2021) Sánchez (2019) Palm *et al.* (2001) INCA-Cuba (2023) INCA-Cuba (2020)
Organic matter of the Floor MOS	Humid oxidation (Walker-Black,1934) ESPECTROFOTOCOLORÍMETRO C UV 559 NM	Canellas y Humosfera (2005)
pH	pH Potenciometría meter PHSJ-3F, 1:2,5: floor; it dilutes	NC:10390, (1999)
Match ppm	UV 900 nm	NC:39 (1999)
Potassium	Flame Fotometría	Paneque (2002)
Nitrogen	Estimate of the N to party of the organic C, relationship C/N	Paneque (2002)
Bioensumos requeted (t/year)	Calculation / it Bases of the estimate	FAO (2017) Palm *et al.* (2001)
Dimensioned of the prosecution capacity in the design of the minibiofactoría (C)	C = profitable? Biomass x process efficiency Coef. efficiency: composted 50% and Bioles 75%	Funes-Monzote, (2008)
Matter prevails for the Minibiofactoría (t/year)	Calculation / it Bases of the estimate	FAO (2017; 2018; 2021)
I design with existent infrastructure Biofabric's Tubular Biodigestor Channels of silos Solar dryer Cutter of natural material It presses hydraulics	Tubular Biodigestor: 20 m3 p/Mezcla manure / vegetal:70:30 \ Composters channels: 4 units of 25x 3,5 m	Noriega (2024) FAO (2017; 2021) INCA-Cuba (2020) INIA-Cuba (2020) MMA-ONU (2021)
Resilience indicators, extension, circularity and agricultural perspectives	Lombricultivo: 20 beds of 1x5m Base methodological for the training in the resiliencia and extension in family properties in Cuba	Casimiro y Casimiro (2018) Casimiro *et al.* (2020) San Juan y Rodríguez (2016) Tauro *et al.* (2018) Lascano (2024) Núñez, 2020 OCDE-FAO (2020)
Economic analysis	Initial investment; costs, infrastructure directness and teams Operative cost: mane de works, maintenance and materials Benefits; I save for substitution of inputs + revenues per sales Indicators: I GNAWED recovery period THEY GO: methodology Bioeconomic	Altieri y Funes (2012) Báez *et al.* (2021) Quiroga (2021)

Table 3. Techniques applied in the participatory workshops

Workshops	Techniques	Purpose	Reference
Workshop 1	Participative DAFO matrix	Identify the strengths, opportunities, weaknesses, and threats related to implementation	(Geilfus, 2022)
Workshop 1	Problem tree	Analyze the causes and effects of the waste problem	GTZ (1998)
Workshop 2	Actors mapping	Define roles and responsibilities in future implementation	Tapella (2007)
Workshop 2	Prioritization matrix	Select the most suitable (digester type, composters, etc.)	Prepared by the authors based on stakeholder criteria
Workshop 3	Reaching a consensus on the action plan	Derivate from the DAFO matrix and problem tree the concrete actions to implement the minibiofactories and social validation	Adapted from Geilfus (2022)

The SWOT matrix allowed for the identification of strategies (SO, ST, WO, WT) that were translated into a consensus-based action plan with 12 activities grouped into: (I) infrastructure adaptation; (II) technology acquisition; (III) training; and (IV) participatory monitoring. This plan formed the basis of the final procedure.

Structuring the Implementation Procedure

Using the information above, a theoretical procedure was developed, structured in five sequential phases using the Deming cycle (PDCA) approach adapted to agroecological systems: (I) georeferencing, preparation, and adaptation of the physical space (selection of areas and conditioning); (II) construction, adaptation, and assembly of technology (biodigesters, composters, management areas, etc.); (III) start-up and operational launch (initial loading, inoculation); A. Pilot level; B. Extension level; and (IV) training and transfer (training for producers). Monitoring and initial adjustments (pilot level). This procedure was presented and discussed with the farm stakeholders in a participatory feedback workshop for its social validation (Geilfus, 2022), where the following adjustments were suggested, agreed upon, and implemented: (I) adaptation of technical language to local terms and everyday usage in the community; (II) modification of the order of some activities according to the seasonal availability of labor; and (IV) incorporation of traditional waste management practices that the stakeholders considered important for conservation.

As a result of this collaborative process, a final version of the procedure was obtained, agreed upon and contextualized to the conditions of the Guayabal farm, ready for implementation in a later stage. It should be clarified that this process constituted the social and participatory validation of the design, but not empirical validation, which would require the implementation and monitoring of the procedure in the field in subsequent studies of the project.

Feasibility Estimates of the Proposal

To evaluate the potential feasibility of the designed procedure, estimates and projections were made based on available information and models referenced in the literature (Table 2):

1. Self-sufficiency in bio-inputs was estimated using a theoretical supply-demand balance: (I) projected supply (organic waste kg/month multiplied by the transformation coefficient (Rodríguez *et al.*, 2020). (II) demand: (estimated bio-input requirements for existing crops kg/month, according to technical doses recommended by the Soil Institute (IS-Cuba, 2023). (III) result of the estimate (projected supply/demand) x 100).
2. Return on Investment (ROI) was projected over the necessary timeframe, estimating the recovery of the initial investment based on: (I) estimated initial investment (cost of infrastructure, equipment, and materials (based on local quotes and experience with similar projects)). (II) projected monthly savings: (I) Current expenditure on external bio-inputs that would be replaced by on-site production. (II) Estimated payback period: initial investment/monthly savings (Gitman & Zutter, 2012).
3. Soil Improvement Project: The potential increase in soil organic matter (SOM) was modeled based on: (I) Estimated application rates: the amount of bio-input that would be produced annually, according to the availability of waste. (II) Response curves; SOM accumulation models referenced in the literature for similar soils with organic amendments (Ponce, 2006). (III) Projected scenario of SOM increase in years.

These estimates do not constitute empirical validation of the procedure, but rather a theoretical approximation that suggests its potential viability and guides future stages of implementation and field monitoring.

Phase III: Data Processing and Analysis

The data were processed as follows: (I) Quantitative: Microsoft Excel 2016 for descriptive statistical calculations (mean, Standard deviation) for soil and residue parameters. The projected improvement of soil organic matter (SOM) was modeled using simple linear regression based on application rates, according to soil condition assessment.

(II) Qualitative: Interviews and workshops were transcribed and analyzed using thematic content analysis (Braun & Clarke, 2006), with support from Atlas.ti 8, indicating emerging categories regarding perceptions, knowledge, and social viability of the model.

Ethical Considerations

Informed consent was obtained from all participants. The confidentiality of personal data was guaranteed, and the results were shared with the community through a socialization workshop.

RESULTS AND DISCUSSION

Farm Characterization and Baseline Diagnosis (Phase I)

The Guayabal farm is located on the Tapaste Road, San José de las Lajas, Mayabeque, Cuba. The geographic coordinates 22° 59′ 55″ N, 82° 01′ 02″ W (Location Code: IPEN 76JXVXRXJ + P3) were georeferenced to locate the sampling points within the farm and facilitate the replication of the methodological study on farms with similar conditions, creating opportunities for collaboration and training with local producers (Geilfus, 2022).

It has a total area of 846.6 ha, larger than the 29 ha for representative farms that occupy 9% of the province, according to studies conducted by Fundora *et al.* (2024). The areas are distributed as follows: pastures occupying 770.4 ha (associated with cattle ranches), bodies of water (lagoons) on 76.2 ha, fallow land on 25.5 ha, and agricultural areas on 100.6 ha.

The productive and agroecological characteristics are as follows: (I) agricultural production on 387.2 ha (in rotation/succession). (II) annual crops in succession: beans-corn-peanuts-garlic-sweet potato-tomato-squash-cucumber-taro. (III) perennial crops (monoculture): plantains, cassava, coconut. (IV) fruit trees (specific diversity): star apple, guava, passion fruit, mango, avocado, mamoncillo, soursop, papaya, lemon. (V) Pastures: high-quality pastures on 43 ha, low-quality pastures on 25.8 ha, and natural weeds on 87.8 ha, serving as a biodiversity reserve. (VI) Agricultural fallow with 89.7 ha. (VII) For Livestock and Forage Production: Pastures (266.6 ha), cultivated forages such as King Grass (25.8 ha), sugarcane (2.8 ha), and a mixture of titonia, moringa, and King Grass (12.5 ha). (VII) The livestock characterization is given in a population dynamic of livestock (Number of Head/year) for cattle: 2021-353, 2022-336, 2023-320, 2024-296, 2025-482 and small livestock (sheep, goats, pigs, rabbits, poultry) between ≈ 313 (2021-2025) in 2025, indicating capacity. Climate data (2010-2025) obtained from the area (Table 1) show average precipitation values of 1350 mm and temperatures of 24.5°C, conditions that determine primary productivity, waste generation and conservation, and potential fluctuations in livestock populations (González *et al.*, 2021).

Among the parameters evaluated for the soil of the Red Leached Ferralitic farm in the studies conducted, the organic matter content of 1.55% stands out, which is low for soils of this Ferralitic composition. The pH was found to be between 7.2 and 7.6 (slightly alkaline), a tendency characteristic of these soil types. Nutrient levels were low: potassium (K) 0.35 cmol/kg (low level), phosphorus (P) 0.95 ppm (very low level), nitrogen (N) 0.10% (low level), and the C/N ratio at 11.98, which is within an acceptable range for mineralization. These results indicate that these soils have characteristics that qualify them as agrogenic, degraded due to inadequate management during their exploitation (Hernández *et al.*, 2014). The available and underutilized physical infrastructure on the farm includes: unused masonry warehouses, both with and without roofs, cement floors, and underutilized prefabricated structures; unused silage areas with potential for repurposing; and perimeter fences. Irrigation infrastructure and water intakes are operational. There are also available artisanal prototypes such as solar dryers, presses, and mills. Biodigester, shredder, pyrolytic oven, and cutting machine are important for biomass processing. These elements constitute a favorable potential base for nutrient recycling and its more economical transformation (Altieri & Nicholls, 2012; Rodríguez *et al.*, 2020).

The multi-year geospatial analysis of the mapping to estimate the Normalized Difference Vegetation Index (NDVI) generated from Sentinel-2 images is shown in Figure 1. This allowed for the explicit spatial identification of the areas with the greatest biomass potential.

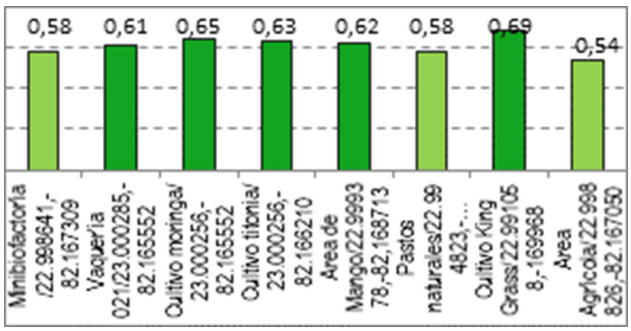


Figure 1. Average values from the multi-year NDVI mapping analysis generated from Sentinel-2 images (2021-2025).

The NDVI reveals the stable photosynthetic capacity of the farm, with average values of 0.57-0.69 depending on the zone. King Grass (NDVI: 0.69), Moringa, and Tithonia (NDVI: 0.65) showed the highest potential biomass, while agricultural areas showed the lowest (NDVI: 0.54), as reported by López *et al.* (2020). The direct correlation between NDVI values (> 0.65) and the intense green coloration on the maps visually indicates the location of key crops for the Mini-Biofactory, such as King Grass, Moringa, and Tithonia, confirming their vigor and plant health. Conversely, areas with yellowish tones (NDVI ≈ 0.54) coincided with agricultural zones with less coverage, reinforcing the need for intervention with bio-inputs.

This interannual consistency observed over the years suggests the productive sustainability of biomass to systematically provide raw materials for production at the Mini-Biofactory; primarily in crops with high nutritional value used for animal feed, the residues of which from this process and pruning can be used as highly nutritious material for the production of agricultural bio-inputs.

The estimate of the endogenous biomass potential, calculated from the weighted NDVI and shown in Table 4, indicates that the farm generates an annual surplus of 2,900 t of biomass (plant matter + manure). The pilot Mini-Biofactory only requires 400 t (13.8%), demonstrating high resilience to variations in availability and a solid raw material potential. When analyzing the demand for bio-inputs compared to production capacity, the former (200 t/year) is lower than the potential production capacity with the assigned raw material (400 t/year); this suggests that surpluses can be produced from the outset for sale or scaling up the process.

The critical negative nutritional balance, such as the nitrogen deficit (-1,205 kg), is more alarming and technically justifies the need to prioritize the endogenous production of nitrogen biofertilizers (compost enriched with Biols). In the transition to food self-sufficiency, the 65% forage content corroborates the successful strategy of reducing external dependence.

Table 5 conclusively summarizes that the Guayabal farm not only has the endogenous potential to implement the mini-biofactory, but that this presents itself as a necessary and technically quantifiable solution to close its nutrient cycles and achieve greater productive sustainability, serving as a replicable model for the region. The endogenous potential of the Guayabal farm demonstrates an optimal relationship between available resources and its internal needs. This would lead to a successful transition from animal feed and agricultural bio-inputs using its own resources.

Participatory Analysis to Generate an Action Plan for the Design of the Proposed Model for Implementing the Mini-Biofactory

Participatory SWOT Matrix

In the initial workshops with key stakeholders, information was gathered and the following were identified primarily through the SWOT matrix analysis:

I. Strengths (S): S1. Farm with a teaching and research function. S2. Availability of waste with a wide diversity of plant and animal raw materials in an area of 846.6 ha. S3. Skilled workforce with a willingness to change. S4. Potential for a production and storage area for the mini-biofactory with disused infrastructure and irrigation. S5. Artisanal prototypes for biomass processing. S6. Technical support provided by the farm's economic management team with specialists and digitalization; electricity is available in all areas.

Table 4. Estimate of the potential of endogenous biomass and calculation - estimate bases

Parameters	Value	Calculation / Basis of the estimate in Total Area (846.6 ha)
Pondered NDVI (Vegetable biomass)	0.65	Dear starting from the mixed covering (active cultivations, grasses, fruit-bearing, perennial, overgrowth). Value> 0.6 indicate vigorous vegetation.
Total Vegetable biomass (t / year)	922	(100.6 have agricultural x 5 t/ha) + (2666.6 have pastes/forages x 2.5 t/ha) + 87.8 have overgrowth x 1.5 t/ha). it Includes residuals of crops, pruning's, surpluses of forages)
Total Animal manure (t / year)	1978	(482 cab. Of bovine livestock x 10 t / year) + (313 Cab. Smaller livestock x 2 t / year). Based in productions stockings for heads.
Bioensumos requirement (t / year) FAO (2017**b**)	200	Calculated to supply 100% of the agricultural area (100.6 have), with a half application of 2 t/ha / year)
Matter prevails for the Minibiofactoría (t / year)	400	I use of 200 t of vegetable biomass + 200 t of manure. It represents alone the 21.7% of the vegetable biomass and 10.1% of the available manure, showing a great margin.
Self-sufficiency animal feeding (%)	≈ 65	Based on the transition 2024-25. I use intensive of 25.8 there is of King Grass (70 t/ha / year) + 5.4 have of Titonia/moringa + natural grasses
Balance NPK - Deficit (kg/año)	N: -1205 P_2O_5: -400 K_2O: -1150	Calculation based on half extraction of cultivations (N; 120, P2O5: 50, K2O: 115) in 100.6 there is, contained Vs of nutritious in the floor (N; 10%, P2O5: 0.95 PPM, K2O: 0.35 cmol/kg)

Table 5. They Summarize of the endogenous potential for the Minibiofactory

Parameters	Value	Potential p / minibiofactory
Total area	846.6 ha	It limbs appropriate for demonstrative model
Vegetable biomass	992 t/año	Matter prevails for compost and Bioles
Animal manure	1978 t/año	Source of N and microorganisms
Floors (MO)	1.5%	It demands bioensumos insured it interns
Available infrastructure	400 m^3	It reduces initial investment in 65%

II. Weaknesses: D1. Animal feed was characterized by a period from 2021 to 2023 where there was a high dependence on external inputs with high expenditures on concentrated feed (approximately 2,755,255.75 - 2,849,246.54 Cuban pesos annually), and a period from 2024 to 2025 with a trend towards a transition to more self-sufficient systems. D2. Need for the application of bio-inputs for agrogenic soils. D3. Dispersed waste. D4. Lack of collection infrastructure and potential areas for its processing.

III. Opportunities: O1. Autonomy on the farm enables self-sufficiency in the process. O2. Institutional support from the scientific complex. O3. Local policies.

IV. Threats: A1. Climate variability. A2. Possible resistance to change from traditional methods. A3. Infrastructure requires adaptation for the new use and faces limitations in financial resources for initial investment.

Strategic SWOT Matrix Analysis and Derived Actions

Based on this analysis, a SWOT matrix was analyzed with all the variables, allowing for the derivation of key strategic actions (Núñez *et al.*, 2020), to implement the plan design, prioritizing a framework for adaptation in other contexts (replicability). A strategic action plan was derived, focused on five crucial phases:

1. SO (F1 + F2 + O2): Design of a network of logistics nodes with institutional support.
2. FA (F1 + F3 + A1): Participatory training program to adapt management practices to climate variability.
3. FD (F4 + D2): Implementation of a mini-biofactory to transform waste.
4. DO (D3 + F3): Establishment of optimized routes using local labor.
5. DA (D3 + D4 + A2): Low-cost, phased implementation (start with pilot nodes and expand progressively, if monitoring is feasible).

Procedure designed for the implementation of the mini-biofactory and logistics network (Phase II)

Based on the previous analysis, a five-phase procedure was structured based on the PDCA cycle (Plan-Do-Check-Act), adapted to agroecological systems by Velandia & Restrepo, (2018): (I) site preparation; (II) construction and assembly of technologies; (III) start-up; (IV) training; (V) monitoring. This procedure was presented and discussed with the producers in participatory workshops with collaborative adjustments, reaching a consensus version in accordance with the principles of the participatory methodology of Geilfus (2022).

Sizing the Mini-Biofactory

Based on the available raw materials (992 t/year of crop residues, weeds, forage, and surplus, and 989 t/year, of which 50% is 1978 t/year, from cattle and small livestock), and considering a low-cost approach, the pilot-phase Mini-Biofactory was sized using the existing disused storage structures. The estimated capacity for the first 1-2 years is to process 200 t/year of bio-inputs, which can cover 100% of the farm's endogenous agricultural needs plus any surplus for initial sale. The estimated capacity for the next 3-5 years, with the addition of silo structures, would be to process 500 t/year of bio-inputs, and it is estimated that this capacity could eventually supply the entire region. These phases are summarized in Table 6.

Table 6. Sizing of the pilot and expansion phase

	PILOT PHASE				EXPANSION PHASE			
Component	**Dimension**	**Area m²**	**Capacity**	**Relative Location**	**Dimension**	**Area m²**	**Capacity**	**Relative Location**
Pre-composting	10 m x 10 m	100	50 t batch	Exterior adjacent to dairy farms	20 m x 15 m	300	50 t batch	Cement floor with drainage system
Main Composting	15 m x 10 m	150	100 t/year	Central courtyard between warehouses	25 m x 15 m	375	300 t/year	Overlapping shifts, mechanical turning
Vermiculture	5 m x 10 m	50	20 t/year humus	North shaded area	10m x 15m	150	50 t/year humus	Automatic drip irrigation system
Biopreparation Processing	8 m x 6 m	48	30 t/year	Covered warehouse 1	12m x 10m	120	80 t/year	Bottling table in the quality control area
Storage/	6 m x 6 m	36	---	Covered warehouse 2	10m x 8m	80	----	Shelving, loading and unloading area
Packaging	4 m x 4 m	16	10 t/year	Semi-covered warehouse	8m x 6m	48	20 t/year	Sealed fermentation tanks

The estimation of the estimated production capacities compared with the internal demand for the farm, which supports its self-sufficiency (Table 7).

The estimated global self-sufficiency of 162% exceeds the 100% threshold recommended by Altieri *et al.* (2015), for considering a biofactory implementation model viable. The surpluses shown in Table 7 suggest a revenue opportunity that could accelerate the return on investment, indicating the model's economic viability. The estimated cost-per-investment analysis for the pilot and expansion phases (Table 8) shows that, although the initial investment and operating costs are $2,750 and $2,500 higher, respectively, in the expansion phase, the net annual profit increases with a payback period of one month.

The return on investment (ROI) of 315% and 345% far exceeds the 15-20% considered acceptable for agricultural projects (López *et al.*, 2020). The ROI value shows that, although the expansion phase involves a larger initial investment than the pilot phase, the efficiency and profitability of the investment relative to the cost are adequate. The rapid recovery estimated at 15-16 months is explained by the use of existing infrastructure and the immediate reduction in input purchases. The silo channel design represents a cost-effective innovation.

Nutrient Cycle Closure

The efficiency in successfully closing the nutrient cycle with the introduction of mini-biofactories for processing waste into bio-inputs is shown in Table 9. Nutritional self-sufficiency was estimated at 162%, representing the production of more than the farm needs. The reduction in losses from 40% to less than 10% overall reflects the 85% efficiency in N and K, which surpasses the 30-40% of conventional systems reported by Havlin *et al.* (1999). The improvement in overall efficiency is estimated at 30% to 40%.

Closing the cyclical nutrient flow represents a transition from extractive to generative agriculture on the farm, where fertility is managed and recycled internally, leading to its sustainability.

Logistics Node Network (LNN)

Optimizing routes for biomass collection and pre-processing with an efficient collection and pre-processing system can minimize transportation costs, which is one of the farm's weaknesses identified in the strategic action plan. It is possible to make the process viable while preserving biomass quality and minimizing the volume of material transported by establishing intermediate nodes or blocks between the biomass source and processing. These nodes would include areas for initial preparation of the plant biomass, such as cutting, drying, packaging, pre-composting, and transformation into biochar in artisanal pyrolytic kilns. It is suggested that these be located in silo structures 720 m from the mini-factory. In addition to preserving biomass quality, this also reduces the direct transport of manure from dairy farms (240-840 m to silos) and allows for pre-composting by mixing it with biomass from moringa/titonia pruning waste located just 400 m away.

Table 7. Production capacities vs. internal demand of the farm

Bio-inputs	Production	Property Claim	Self-sufficiency	Surplus
Compost (t/year)	300	200	150%	100
Bio-fertilizers (L/year)	150 000	100 000	150%	50 000
Humus (t/year)	100	50	200%	50
MEM	10 000	5 000	200%	5 000
Biochar (t/year)	9	8,2	100%	0,8

Table 8. Investment and return analysis

Parameters	Pilot Phase	Expansion Phase
Initial Investment USD	$4 000	$ 6 750
Annual Operating Costs USD	$5 800	$8 300
Annual Net Profit USD	$14 200	$23 300
ROI %	315	345
Payback Period (months)	16	15

Table 9. Efficiency in closing the nutrient cycle

Nutrients	Annual extraction	Mini-biofactory Recovery	Closure Efficiency/Medium
Nitrogen (N)	1 459 kg	1 232 kg	85-90% (in composting + biodigester)
Phosphorus (P)	580 kg	420 kg	70-75% (less losses due to leaching)
Potassium (K)	1 380 kg	1 173 kg	80-85% (in biofertilizers and compost)
Organic Matter -OM	3 200 kg (estimated for soil losses)	2880 kg	90-95% (in substrates with compost + biochar)

The estimated reduction in the volume of transported material found to be between 30-50% for viable routes was identified.

The following routes are suggested: (I) Route 1. Dairy farms - silos (pre-composting) - Mini-biofactory. (II) Route 2. Pasture and crop areas - intermediate collection points - Mini-biofactory. (III) An intermediate collection point on agricultural land 750 m from the mini-biofactory for plant biomass, where the average transport distance would be 500-1000 m for plant biomass and 700-1500 m for manure, according to the optimized routes. The suitability of the location of the artisanal technologies (biodigester, solar dryer, shredder, cutter, pyrolytic ovens) is related to the existing process, according to the most viable suggested routes and the location of the intermediate pre-composting mini-factory.

Four groups were designed according to their location (pre-processing mini-factory, optimized routes to transport the biomass to them), forming blocks or nodes: (I) mini-biofactory (Phase 1: Center and 2: North). (II) optimized routes (Phase 3: Central optimized route). (III) hybrid (Phase 4: contains the mini-factory and optimized routes). The design and characterization of each block or node (South, Center, North, and hybrid) are detailed in Table 10. This table shows subdivisions within the proposed design into modules for each block or node, which would guarantee the viability of the work within them. In the case of the hydride node, it is strategically located according to the biomass flows.

The optimized route collects waste from nodes in a single weekly trip (Figure 2).

With this network, an estimated 67% reduction in trips (from 15 to 5), a 60% reduction in fuel consumption (from 120 L to 48 L/week), and a 60% reduction in working time (from 25 to 10 hours/week) were achieved. The procedure at the nodes improves homogeneity and reduces putrefaction, thus improving the quality and volume of biomass to be transported, which increases the efficiency of bio-input production. This logistical approach has not been widely adopted in previous Cuban experiences (González & Martinez, 2019; Pérez *et al.*, 2021), where biofactories are studied as isolated units.

Table 11 shows the estimated comparative profitability for each strategy. The hybrid strategy, which combines the mini-biofactory blocks and the routes, is the most efficient, yielding a maximum production of 99 t/year vs. the projected 27 t/year, savings of $290 USD vs. $630-1360 USD, and a return on investment (ROI) of 1.35% with a 3-day payback period, suggesting the viability of the proposal. The greater resilience of the three independent systems is noteworthy. The block structure allows the others to continue operating even if one fails or in contingency scenarios (extreme rainfall, power outages, staff shortages), illustrating the adaptability and flexibility of the proposed model.

Feasibility estimates for implementing the mini-biofactory at the Guayabal farm

Based on the estimated endogenous biomass (10.2 t/year) and referenced models, the following was projected: (I) 162% self-sufficiency in bio-inputs (supply/demand), higher than the 120% reported by González & Martinez (2019), due to the greater waste generation at Guayabal. (II) a return on investment (ROI) of 16 months, within the range of 14-18 months found by Pérez *et al.* (2021) in the province of Granma, Cuba. (III) Soil organic matter improvement was estimated to increase from 1.55% to 4% over three years, consistent with soil organic matter accumulation models (Ponce, 2006) and with agroecological principles (Altieri & Nicholls, 2012; Altieri et al., 2015). (IV) Self-sufficiency in animal feed is estimated to improve by 31%, which agrees with the findings of Funes-Monzote (2008) for Cuban agroecological systems on local farms. (V) Projected external dependence is expected to decrease by 81%, generating resilience to market fluctuations.

Table 10. Network of Logistics nodes and waste generation points

Node	Coordinates	Function	Power generation points supplied	Main Residue
South (S)	22 992500-82 170200	Phase 3. Transport to the central area. Collection and pre-processing for shipment to the central mini-biofactory.	Southern dairy farms, southern farming areas	Cow manure, crop residues, weeds
Center (C)	22 988800-82 167000	Phase 1. Pilot Central Minibiofactory. (1.5 ha: 3 modules). Initial waste processing for bioinputs production.	Areas near the central pilot biofactory.	Cow manure, nearby crop residues
North (N)	23 001000-82 164900	Phase 2. Extension minibiofactory (2 ha: 4 modules). Additional waste processing to supply more areas.	Northern dairy farms, northern farming areas	Cow manure, titonia, moringa, stubble
Hybrid	Strategic location according to traffic flow	Phase 4. hibridy node that combines minibiofactory + optimized route. It processes 1325 kg/d using north and south flow.	North and South flow from multiple areas.	Dispersed plant biomass (pruning, stubble, titonia, moringa)

Table 11. Estimated comparative profitability for each strategy

COMPARATIVE PROFITABILITY			
Investment	$1,360 USD	$860 USD	$290 USD
Savings	+ existing resources + $1,070 vs. Mini-biofactories	+ $340 vs. Routes	$1,070 vs. Routes $340 vs. Mini-biofactories
Annual Costs ($)	1 300	1 620	2 660
Net Profit (USD/year)	13 900	13 580	43 825
Annual ROI (%)	1,022	1,579	1,350
Recovery (months)	1,2	0,8	0,08

The economic balance (USD/year) projects a progressive improvement seven times greater than the initial percentage value, which corresponds to the findings of SAFE (2002), for farm production systems.

Scope and value of the study

The main achievement of the study is having obtained for the first time, in the context of the Guayabal farm with its educational teaching character and its high institutional articulation, an original, participatory and contextualized methodological procedure for the implementation of a mini-biofactory of bio-inputs that integrates a georeferenced logistics network (Figure 2).

Figure 2 shows the spatial distribution of the four intermediate nodes that make up the logistics network. The central node (phase 1) operates as a pilot mini-biofactory with 1.5 ha and 3 internal work modules. The northern node (phase 2) operates as an extended mini-biofactory (Silo Structures), with 2 ha and 4 internal work modules. The southern node (phase 3) is dedicated to the collection and transport of waste from more distant locations to the central area. The hybrid node (phase 4) combines processing in mini-biofactories with an optimized route, with an estimated production capacity of 1325 kg/d. The solid brown arrows (manure) and dashed green arrows (biomass) indicate the flow of waste from the source (dairy farms, cultivated areas, and field edges) to each node. The main optimized route (thicker blue dashed lines) connects the nodes in a circuit (south-central-north-hydro), reducing travel, fuel, and time by 60-67%. An alternative arrow (lighter dashed line) allows for optionally closing the circuit from the hybrid node to the south, depending on the amount of biomass available. Finally, the green dotted arrows represent the return of bio-inputs (compost, biofertilizers, biochar, extracts) from the processing nodes to production areas, closing the nutrient cycle.

This cyclical model aligns with the best practices of the circular economy referred to by Villalpanda (2024) and is projected in three fundamental implementation phases:

> PHASE 1 (0-6 months), pilot implementation, as a basic mini-factory. Establish a pre-composting area in silage structures at a distance of 720 m as an extension. Implement optimized collection routes and establish intermediate nodes, using geospatial analysis.
>
> PHASE 2 (6-18 months): Operational scaling up, develop specific bio-inputs for the existing soils according to their conditions. Establish training programs for local and community producers, based on their educational level. Implement a systemic quality control and monitoring system.

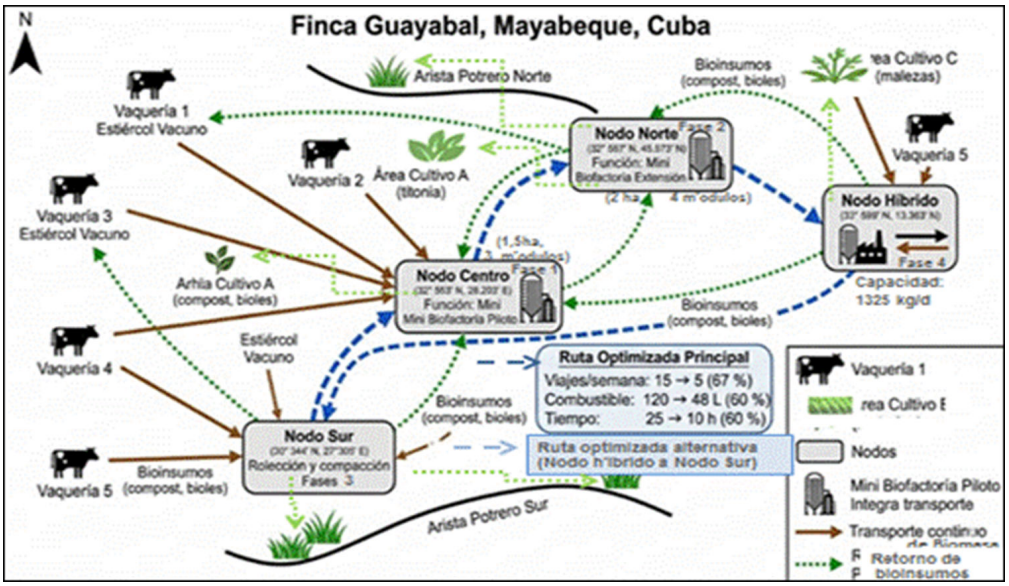


Figure 2. General scheme of the logistics network for the implementation of the mini-biofactory on the Guayabal farm.

PHASE 3 (18-36 months): Consolidation of implementation. Transform the farm into a national reference center. Develop a replication model for different production scales. Establish a bio-input marketing network in the region (González, 2023).

The proposed model is a tool that is not yet widely used, built on the farm's specific conditions, but designed with an adaptable and replicable approach for other local farms that share agroecological principles and the need to close nutrient cycles. As this is a prospective study, the feasibility estimates presented are theoretical projections that will need to be empirically validated in subsequent stages. Far from being a limitation, this condition defines the pioneering nature of the work and establishes the methodological foundation for future implementations in the region.

CONCLUSIONS

- The Guayabal farm possesses the technical, economic, and social conditions necessary for the successful implementation of a mini-biofactory for agricultural bio-inputs. The proposed design guarantees 162% self-sufficiency with a return on investment in 16 months, demonstrating high profitability.
- The nutrient cycle closure achieves efficiencies of 85% for nitrogen and potassium, surpassing conventional systems. The phased replication strategy is estimated to impact approximately 45 producers over 3 years, multiplying the demonstrative effect.
- The model constitutes a viable alternative for food sovereignty and agricultural sustainability under local conditions. For future research, the following is recommended: (I) standardizing quality protocols for the agricultural bio-inputs obtained; (II) developing local carbon markets for soil carbon sequestration; and (III) conducting comparative life cycle studies with commercial chemical inputs.

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