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Integrated procedure for optimization of self-sustaining management of nutrients and wastes on farms in Mayabeque

Procedimiento integrado para la optimización del manejo autosostenible de nutrientes y residuos en fincas de Mayabeque

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ABSTRACT: The objective of this research was to propose a procedure to integrate practical and adaptive self-management solutions in the management of nutrient flows, taking advantage of endogenous waste on local farms in Mayabeque, thus contributing to the transition towards a self-sustaining circular economy. The procedure was based on: (I) the determination of endogenous potential for waste generation and the limitations in the recirculated nutrient flow; (II) the identification of strategic actions; (III) the design of a comprehensive adaptive procedure. A procedure is derived that articulates a cyclical adaptive system of nutrient flows from endogenous waste generated, recirculated, and integrated into the production process on a local farm, to ensure the basis for self-management in the production of agricultural bioinputs with accessible technologies. The estimated total investment benefits were approximately $485 USD for La Esperanza and $1280 USD for Nuestra Señora. Self-sufficiency in animal feed increased by 95% on the first farm, while on the second farm, N and K deficits were reduced by 50% through more efficient waste management.
Keywords: Recycle, Organic Waste, Circular Economy, Composting, Bioproducts, Sustainability.

RESUMEN: El objetivo de esta investigación fue proponer un procedimiento para integrar soluciones prácticas y adaptativas de autogestión en el manejo de flujos de nutrientes, aprovechando los residuos endógenos en fincas locales de Mayabeque, contribuyendo así a la transición hacia una economía circular autosostentable. El procedimento se basó en: (I) la determinación de las potencialidades endógenas para la generación de residuos y las limitantes en el flujo de nutrientes recirculados; (II) la identificación de acciones estratégicas; (III) el diseño de un procedimiento integral adaptativo. Se deriva un procedimento que articula un sistema cíclico adaptativo de flujos de nutrientes de residuos endógenos generados, recirculados e integrados al proceso productivo en una finca local, para asegurar la base para la autogestión en la producción de bioensumos agrícolas con tecnologías accesibles. La estimación de los beneficios en inversión total fue de aproximadamente $485 USD para La Esperanza y $1280 USD para Nuestra Señora. La autosuficiencia en la alimentación animal se incrementó en un 95% en la primera finca, mientras que en la segunda se redujo el déficit de N y K en un 50% mediante un manejo más eficiente de residuos.
Palabras clave: reciclaje agrícola, residuos orgánicos, economía circular, compostaje, Bioproductos, sostenibilidad.

INTRODUCTION

Currently, great importance is placed on the agroecological study of production systems as a basis for studying, establishing, and adopting new technologies and developing a sustainable circular economy, taking into account existing endogenous conditions. This is what Fundora *et al.* (2024), described with their agroproductive characterization study on 57 farms in the Mayabeque province. They present essential challenges to address, such as the high incidence of pests and diseases, the scarcity of herbicides, chemical fertilizers, organic fertilizers, and biofertilizers as nutritional alternatives, cost reduction, increased productivity, and the possibility of import substitution. They point out that very few producers establish actions that integrate self-management as a basis for mitigating these limiting factors. Hence the importance of strengthening education and adopting technologies alongside producers that promote the efficient use and integrated management of local nutrient sources. This should be achieved according to the circumstances, limitations, and capabilities of the farms (Rivera *et al.*, 2020).

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Among the most current actions to achieve integrated management of local sources is the establishment of biofactories on farms with the adoption of cyclical models of self-sustaining production of agricultural bioinputs, based on the recycling of biomass generated on farms. This approach is not yet widespread on Cuban farms. Achieving implementation with a model based on long-term circular economy indicators in agriculture allows for the adoption and measurement of the degree of "circularity" associated with waste management (Quiroga, 2021). This is possible through the application of the precepts of circular agriculture in the agroecosystem: (I) Reducing the amount of inputs into the system of chemical fertilizers, pesticides, and scrap metal and plastic equipment. (II) Reducing water use and pollution. (III) Reducing emissions during production cycles. (IV) Reusing and adding value to biomaterials perceived as waste. (V) Exerting the least possible pressure on the environment and natural resources (water, air, nature, and biodiversity). (VI) Healthy soils. (VII) Agroecological pest management.

The circularity of the model is based on the processes of reusing, repairing, or recycling all types of resources and waste to reintroduce them into sustainable production systems, achieving process optimization without generating waste and contributing to environmental protection (Villalpanda, 2023; 2024). This is a challenge in the agricultural sector, where production is more demanding and requires more efficient alternatives to continue advancing productive and environmental sustainability; with support for the development of the sustainable development goals set out in the 2030 Agenda by the OCDE-FAO (2020).

Composting and fermentation, as controlled biological processes that mimic the natural cycle, have a comprehensive approach that contributes to reducing waste generation and promoting the reuse of materials, giving them a more up-to-date use value in circular biofactory models (MMA-ONU, 2021). In this way, the waste of waste with a high generation of organic waste is avoided and the reuse of materials that can be improved in nutritional quality is promoted, resulting in immense productive advantages by having varieties of bioproducts that allow for self-sustaining agroecological and environmental management. These bioprocesses have become centers for providing an adequate solution for waste validation and establishing comprehensive and sustainable nutrient management on farms. This constitutes a major challenge based on the introduction of the circular economy model, which links a series of goals to the advancement of the Sustainable Development Goals. Through these goals, nutrient and organic matter cycles can be closed to achieve comprehensive waste management, creating a more sustainable and efficient production system.

The development of these goals has currently generated greater interest worldwide (Mexico, Chile, Colombia, Brazil, Ecuador, the United Kingdom, Spain, and the United States) in the development of these low-cost processes in cyclical production models of biofeeds in on-farm biofactories to generate self-profitability through a more competitive process (Restrepo, 2007).

However, this goal is not widely recognized in the specialized literature in Cuba. There are extensive references to water treatment, according to Díaz *et al.* (2022) and as biofactories for the production of vitro plants and seeds Noriega (2024); but it does not appear as an integrated model system.

The basis for its implementation lies in the endogenous potential for managing the waste generated on these farms, enabling it to be implemented as a profitable model with viable and sustainable comprehensive solutions, providing an opportunity to add value to waste. This reduces the negative environmental impact, increases agricultural productivity with quality, and promotes self-sustaining agroecological management.

This is the basis for implementing biofactories for the production of low-cost agricultural bioinputs on local farms, ensuring their self-sustainability. It emerges as a viable alternative for improving self-management for the development of a territorial human and animal food self-sufficiency program in harmony with the environment, under the development of Circular Ecological Agriculture.

The objective of the research was to propose a procedure that integrates practical and adaptive self-management solutions for managing nutrient flows with the use of endogenous waste on local farms with a characteristic agricultural composition of the Mayabeque territory, contributing to establishing the transition toward a self-sustaining circular economy.

MATERIALS AND METHODS

The case study was conducted (2021 and 2023) on two local farms in San José de Las Lajas, Mayabeque municipality. These farms have an area and agricultural composition typical of the region (Fundora *et al.*, 2024). Their social objective is the production of root vegetables, fruits, grains, and greens. The livestock consists of small-scale dairy and beef cattle, laying hens, rabbits, goats, and pigs, all dedicated to facilitating food self-sufficiency in the locality. They are also often a place of tourist interest due to their rural and peaceful atmosphere typical of the Mayabeque area. For the study, two representative farms (area and climatic variations/year) were selected from the largest percentage groups in the locality reported for 57 farms in the Mayabeque area by Fundora et al. (2024).

Some characteristics of the study farms are described in Table 1.

The annual average climate data for San José de las Lajas, Mayabeque, were recorded by the Cuban Meteorological Institute INSMET-Cuba (2024), these data are used to estimate biomass and are presented in Table 2.

The work procedure consisted of the following fundamental steps: (I) Determine the existing endogenous potential on farms for waste generation and the limitations for developing the recirculated nutrient flow

Table 1. Characteristics of the study farms

Farm	**La Esperanza**			**Nuestra Señora Regla**		
Location in San José de las Lajas, Mayabeque	Tapaste Highway, km 3, 1.2 km, Nelson Fernández CCS			Zenea Highway. Manuel Fajardo CCS		
Area (ha)	3			19		
Representativenes within the province	Group of farms with the highest percentage (38%), of those studied in the province with smaller areas (0.1-9.5 ha)			Group of farms with areas between 19 and 20 hectares, representing 16% of the farms studied in the province		
Crops grown and management	Cultivated in succession: beans-corn-peanuts-garlic-sweet potato-tomato-squash-cucumber-beans-fallow land. Perennial monocultures: plantains, cassava, taro, grasses, canavalia. Fruits: star apple, guava, passion fruit, mango, avocado, mamoncillo, soursop, coconut, papaya.			Pastures, fruit trees: guava, mango, avocado, soursop, banana, coconut, papaya, sour orange, and lemon. The crop sequence is: corn, beans, corn, soybeans, tomato, squash, beans, corn, cucumber, beans, corn, and chili. Grazing and fallow		
Animal Breeding	6 cows, 50 rabbits, 25 chickens, 20 pigs, 2 oxen			15 cows, 50 rams, 30 chickens, 25 pigs, 2 /oxen		
SoilsRed Ferralitic (2021)	pH 7.2	%SOM 1.5	K 0.35 cmol/kg	pH 6.31	%SOM 1.47	K 0.6 cmol/kg
	P 0.95ppm	N 0.10%	Rel. C/N 11.98	P12 ppm	N 0.09%	Rel. C/N 12
SoilsRed Ferralitic (2023)	pH 7.6	%SOM 2.53	K 0.45 cmol/kg	pH 6.5	%SOM 2	K 0.8 cmol/kg
	P 12.3ppm	N 0.13%,	Rel.C/N 12	P 15ppm	N 0.12%	Rel. C/N 12.2
Compost application (2023)	8-10 t/ha and 0.5 t/ha ash/5 t compost			≈15 t/ha and 0.5 t/ha ash/5 t compost		

Table 2. Annual average climate data recorded for the San José de las Lajas, Mayabeque area INSMET-Cuba (2024)

Parameters annual means	**Year 2021**	**Year 2023**
Precipitation mm	900 (less than 5% vs historical data 30 years old)	1500 (less than 20% vs historical data 30 years old)
Temperature °C	26,65 (Tmax.+ 3 °C on the historical stocking)	25,5 (+ 1 °C on the historical stocking)
Relative humidity	75 %	82%
Evapoperspiration	1500 mm	1700 mm
Solar radiation	1700 kWh/m^2	1900 kWh/m^2
Speed of the wind	10 km/h	15 km/h
Extreme events	Moderate drought Julio-August: 33-34 °C	Intense rains August: 177 mm, 32 °C

that enables the comprehensive use of the endogenous waste generated on them. Application of information tools (interviews, surveys, SWOT matrix). (II) Estimate the biomass potential available on farms for use. (III) Identify work strategies based on the farms' endogenous conditions that enable the most efficient and sustainable use of waste. (IV) Design a comprehensive methodological procedure that links endogenous and adaptive strategic actions on local farms with typical composition, integrating the nutrient flow cycles of endogenous waste to give it use value in bioinput production. The actions carried out can be structured into phases, based on information tools: surveys, interviews, participatory workshops, GIS for zoning, and economic data on agricultural and livestock production:

1. Participatory diagnosis: This was developed using the Participatory Action Research (PAR) methodology, with workshops with local stakeholders, producers, researchers from the scientific complex, and cooperatives to analyze endogenous conditions with socio-productive characterization: identifying natural resources (soil, water, biodiversity, and existing biomass), available technological infrastructure, and labor, main crops, livestock systems, and current practices (San Juan & Rodríguez, 2016). The empirical method was applied in the semi-structured interviews with variables suggested to the workers (Villarreal & Cid, 2022).
2. Information provided by specialized literature in studies conducted on local farms in the Mayabeque province (Casimiro, 2016; Casimiro & Casimiro, 2018; Báez *et al.*, 2021; Rodríguez, 2022; Fundora *et al.*, 2024).
3. Based on the information obtained in the previous steps, problems and potentialities were identified through a SWOT analysis (strengths, weaknesses, opportunities, and threats) of the farms' conditions, according to the methodology proposed by Nogueira *et al.* (2024).
4. Estimation of the farms' biomass potential for use as raw material in the production of bioinputs. The procedure followed to estimate the biomass generated on farms in 2021 and 2023 is shown in Table 3, along with the tools, methods used, and their bibliographic references. The methodology described was derived from the integration of procedures reported in the specialized literature.
5. Self-sustainability analysis of farms with generated biomass. To determine whether a farm is sustainable using its own biomass for animal feed and agricultural bioinput production, a procedure was structured based on research methods and concepts used in agroecology, sustainable farm management,

Table 3. Methodology used to estimate plant and animal biomass on farms

Step	Tool / Method	Function	Indexes Bibliographical
1. Determination of space data of the properties with images satelitales	GPS Sentinel-2 (B4-RED,8-NIR, 10m head.)	Obtaining of ghastly bands (NET, NIR) 2021-2023 Calculations NDVI + zonal Statistics	USGS (2024)
2. Calculo of the index of vegetation differential normalized prom. pondered.	NDVI (QGIS + SCP PLUGIN) NDVI + generic correlation (\ (R^2 + 0,68-0,79 \), for native species. Google Earth Engine	To calculate vigor Veg. NIR - NET NIR+RED Temporary analysis NDVI	Costo et al. (2020)
3. Aplicación of Model Alometrics (MA) en agro ecosistems cubans MA + statistcs	Model Alometrics Biomass B B FRUIT-BEARING = 112,5 X NDVI-18,3 (\ (R^2 = 0,81 \) B GRASSES =2,5 X NDVI + 0,8 Annual B Cultivate a = 1,8 x EVI-0,3 R STUDIO	To transform NDVI into biomass (t/ha).	González et al. (2021) INIVIT-Cuba (2023) Dengsheng et al. (2016)
4. Validation of the Biomass estimated by stelite with the certain one for agronomic data	Methodology for cultivation type starting from the determination of the harvest (IC index) Scaling in sowing the area (Information of the Farmer 2021 and 2023). Economic yield Conversion to total Biomass Adjust for handling Comparison with the dear biomass for Sentinet-2 (error ?15%)	Agricultural GPS + QGIS R: Production / ' area index of Crop (IC) = chart BMT = R/IC Coefficient of stress hydric Adjusted biomass (Baj) Baju = Biomass x (1 - %d'eficit hídrico	Taiz (2025) Guía metodológica IPCC (2019)
5. Ajuste climatic	Data climatic averages of San José de las Lajas, Mayabeque, Cuba Data INST. MET. Cuba	To correct biomass for drought / hurricanes	INSMET-Cuba (2024),
6; Calculi End Total Biomass of the property	Pondered area	Total Biomass (BT) BT =? (area x biomass)	USGS (2024)

Legend: BMT-Total Biomass (t/ha), R- Yield (t/ha)

and the circular economy. Its approach was comprehensive and practical, based on specialized scientific studies reported in the literature, and adapted to farms. To assess the self-sustainability of the process, a study was also conducted with the application of bioinputs obtained by farm producers in 2023.

Table 4 reflects the indicators included and the bibliographic citations that support them.

RESULTS

The annual average data for the years evaluated for the San José de las Lajas area, Mayabeque, are reflected in Table 2. These data suggest the occurrence of climate stress.

In 2021, a moderate and prolonged drought was evident, with water shortages in crops (June-September), determined by a 25% reduction in rainfall compared to historical averages, with a 75% lower humidity and greater solar radiation (5%). Maximum temperatures were slightly higher by 0.3%. On both farms, the effects were less severe on short-cycle succession crops due to the use of irrigation to supplement rainfall, according to producers. This was not the case for pastures and fruit trees. For 2022, rainfall remained erratic, with peaks during events (Hurricane Ian and troughs), which caused abundant rainfall (higher and irregular than the historical average for the area) and high humidity.

In 2023, humidity was high (82%), with fewer hours of sunshine (6%) due to persistent cloudiness; and more intense heat with temperatures rising 10°C above the historical average. Rainfall increased by 25%, reaching extreme levels in August (177 mm + 130%) compared to historical data with local flooding. The trade winds were stronger, carrying higher moisture content. It was a year with indirect effects of climate change or specific frontal systems such as Tropical Storm Phillippe and tropical waves that generated intense rainfall. These post-climate effects have repercussions and can impact biomass formation in the areas.

Information collected on farms to determine existing endogenous potential. Analysis using the SWOT matrix

With the information collected and processed from the results of interviews, participatory workshops with farm producers, and specialized literature, strengths, weaknesses, threats, and opportunities were identified through analysis of the SWOT matrix summarized in Table 5.

By conducting the SWOT analysis, a strategic analysis is obtained to establish appropriate actions:

1. FO (Strengths + Opportunities): Use waste to produce agricultural bio-inputs for local consumption and/or to cover external needs. Develop eco-tourism by demonstrating the waste cycle for validation as bio-inputs.
2. DO (Weaknesses + Opportunities): Manage a low-cost model to acquire bio-input production technology with validation of endogenous waste. Identify cyclical pathways for the sustained management of endogenous waste generated on the farm and in the locality for the low-cost production

Table 4. Indicators used to estimate the sustainability of farms with biomass generated

Indicators	Procedure	Methods	Index mentioned
Annual dear biomass (t / year)	Evaluation biomass: Vegetable biomass Animal biomass (manure)	B. Vegetable. Satellite-2/NDVI. Model alométricos. Validation with non destructive Method of field (economic Yield, cultivation type with crop index IC), scaling in planting area). B. Manure: Analysis for integrated properties (agriculture-cattle raising-forests).	Chave et al., (2014) IPCC (2019) Fernández (2020) FAO (2022)
Self-sufficiency alimentary animal%	Annual requirement (t /year) It demands animal Feeding (t / year)	Alimentary balance Methodology to evaluate alimentary self-sufficiency in cattle systems.	FAO (2018) FAO (2021; 2022)
Print of the Carbon (t CO2 eq/ha)	Determination of the kidnapping, emissions and Balance of Carbon.	Based in Standard of IPCC, 2019 and adapted to tropical agricultural systems.	IPCC (2019)
Organic matter of the floor%	Humid oxidation Spectrum picture colorimeter UV, (559 nm)	Walker-Black,1934	NC:10390 (1999)
pH a 25^{0}C	pH meter PHSJ-3F, 1:2,5: soils; it dilutes	Potenciométrico	NC:39 (1999)
It demands bio unsummons (t / year)	Extraction determination of nutritious for cultivations (kg/ha / year) with chart of requirements. To calculate nutrients contributed by bio unsummons.	Analysis of the recycle of nutritious (NPK), comparing the nutrients for cultivation (kg/ha/ year), using requirement chart.	FAO (2021) Paneque (2002) Sánchez (2019) Palm et al. (2001) INCA-Cuba (2023)
Percentage of self-sufficiency%	To recycle of residuals%	Relationship and / biomass produced / nutritional demand (ANIMAL, CULTIVATIONS) sostenibilidad index (0-100%)	FAO (2021) González et al. (2023) Altieri (2002) FAO (2016) Azapagic (2003) INIA-Cuba (2020)

Table 5. Results of the applied SWOT matrix

Category	Internal factors (Strengths and Weaknesses)	External factors (You threaten and Opportunities)
STRENGTHS	Generation of residuals. of stocking to high with high biodiversity levels. Develop of the research and innovations inside the scientific complex. The producers are contained by the CCS, what can facilitate the development of activities participativas with them. The producers have watering systems. Generally productive soils. Necessity of employment of organic payments	**OPPORTUNITIES** Discharge demands growing of bio inputs in Mayabeque. Use of the endogenous residuso for the self-management of bio agricultural ensumos. Existence of producers linked to centers and investigation projects. The producers have the assignment of inputs for the MINAG, but not in a systematic way. You program state support Cubans to the economy (task life, project of local development). Potential for the educational tourism (sustainable routes).
WEAKNESSES	Little culture in the knowledge of the material potentialities of the property for the use of the residuals generated in her. Limited infrastructure for the prosecution of the residuals. Low technification in handlings of residuals to guarantee their maximum use. Nutritional quality of the composting with little use (not developed Vermicomposting). Limited application of technologies of low cost. The fertility of the floor and quality of the waters one works empirically (experience) and not with monitored analysis. Preference of the producing ones to use chemical products that their own organic payments. Little use of green payments. Little culture in the handling of having integrated of nutritious. Scarce registration culture and quantification of residuals	**THREATS** External climatic events that affect the production and gathering of the biomass. Dependence and difficulties in the acquisition of external inputs. High production costs. Bureaucracy in permits for innovative projects.

of bio-inputs. Create composting stations. Introduce a circular model for a low-cost bio-factory for the production of bio-inputs. Train stakeholders in the circular management procedure for endogenous waste on the farm through participatory workshops with local and endogenous stakeholders.

3. Strengths + Threats: Create a Biomass Bank by identifying the cycles in which waste is generated and how it can be reused on the farm. This will mitigate negative impacts, such as climate impacts.
4. Weakness + Threats: Ensure partnerships with other farms to develop a bioinput market or provide training on the topic. Implement a monitoring system for waste quantification. Provide services related to the design of nutrient flow cycles on the farm according to the farm's endogenous resources.

These results correspond to those obtained by Fundora *et al.* (2024), in the characterization of 57 local farms in the Mayabeque province, where the comprehensive assessment of the SWOT matrix results identified the need to intensify training and other innovative actions with farmers so that they can promote the integrated use of bioproducts with local nutrient sources, green manures, quality seeds, soil analysis, and fertility maintenance with increased productivity. The results showed the priority given to adopting strategies based on agricultural snowmaking on farms for the integrated management of soil fertility, with the use of integrated bioproducts and local nutrient sources. This provides sustainable agricultural practices by creating crucial spaces for training and exchange between producers, extension workers, and researchers.

Estimation of the potential for exploitable endogenous biomass on farms

The normalized differential vegetation index (NDVI) value estimated using satellite image analysis data validated by agricultural methodology (by crop type) to measure "green health" on farms is represented in Table 6. The values of 0.43/0.39, in the range of 0.1-0.5 for a farm such as La Esperanza, suggest a vegetation composition characterized by grass, fallow land, and young crops. This value is lower compared to that of Nuestra Señora farm (0.56/0.46), which are described for much denser and more developed fruit trees and trees (0.6-0.8); these values are validated with those reported in studies of 45 farms in Mayabeque during post-stress events obtained using the same methodology (Diaz *et al.*, 2020; González *et al.*, 2021).

On both farms, NDVI values decreased from 2021 to 2023, by 9.3% for La Esperanza and 17.9% for Nuestra Señora, falling within the acceptable range of decreases for forests and fruit trees, between 15-30%; for La Esperanza, between 10-25% for short-cycle and young crops in post-climate stress studies (López *et al.*, 2020).During the study phase (2021-2023), Cuba was affected by climatic events that caused a moderate but persistent drought and abundant rainfall, which could have impacted biomass production in 2023.

The total estimated biomass for farms from 2021 to 2023 shows a similar trend (Table 6). La Esperanza decreased values by 11.12%, falling within the lower limit of the 10-40% biomass decline, with a recovery time of 3-6 months in crops where taro/banana/grasses/annual crops predominate (Diaz *et al.*, 2020). For Nuestra Señora, the decline was 16.1%, falling outside the 40-60% biomass decline range reported by these authors.

Table 6. Estimated biomass potential and integrated sustainability analysis on the “La Esperanza” (3 ha) and “Nuestra Señora” (19 ha) farms for 2021 (without biofeedstock application) vs. 2023 (with and without biofeedstock application).

Parameters	La Esperanza (3ha) (2021 vs 2023)	Nuestra Señora. (19 ha) (2021 vs 2023)
Weighted Average Normalized Differential Vegetation Index (NDVI)	0,43/0,39	0,56/ 0,47
1. Total Biomass (BT) (t/yr)	150,77/ 134,10	109,8/225,4
Plant	140,0/125,0	100,0/200,0
Animal Manure	10,77/9,10	9,8/25,4
2. Requirements	NPK	NPK
Crops (NPK kg/ha)	108, 15, 90/96,12,90	90,27,139/81,26,136
Animal Feed (t)	42,3/45,6	78,2/85,6
Bioinput Demand (t/yr)		
3. Self-Sufficiency	71/78	55/82
Animal Feed (%)	-90, -27,-139/-21, -11,-111	-270,-72, -414/181,-51,-386
NPK Deficit Balance (kg)		
4. Soil Indicators	1,8/2,53	1,3/1,7- 2,53
Soil Organic Matter, SOM (%)	12/12	11,95/12-12,2
C/N Ratio	-1,2/-4,5	-15,7/-12,1
Carbon Footprint (CO2eq/ha)	65/88	45/75
Waste Recycling (%)		
5. Bioinput Production	15/17	15/35
Compost (t)	2,000/3000	2000/3000
Biol (L)		
6. Self-Sufficiency with Bioinputs	85/95	71/95
Animal Feed (%)	-60, -5,-80	-150,-30,-300/-50,-10.-200
NPK Deficit Balance (kg		

The lower incidence and/or recovery process over time may also be related to the application of compost (in a ratio of 5 t compost: 0.5 t/ha ash) by producers using their own waste. This may have contributed to complementing the trend toward biomass recovery, although it only covers approximately 50% of the estimated overall bioinput demand for each farm (Table 4). For soils with NPK deficiency, the application of 5-20 t/ha of compost is suggested (Paneque, 2002).

Abundant rainfall generally favors rapid growth and biomass production; however, waterlogging can damage roots, reduce soil oxygen, and promote fungal diseases in plants, decreasing useful biomass. This is compounded by the challenges of managing residues due to moisture, in addition to physical damage from crushing and breakage. Humid conditions favor explosive weed growth, which competes with desirable crops and pastures. Excessive rainfall can leach nutrients such as nitrogen from the soil (leaching), reducing its long-term availability to plants. The nutritional quality of biomass may be lower in nutrients (proteins and minerals) due to rapid water-driven growth and higher moisture content.

These authors Fernández (2020); González *et al.* (2021), propose as fundamental factors that determine biomass losses in Mayabeque due to post-climatic events: (I) The type of red soil (Red Ferralitic) that has low water infiltration, causing prolonged flooding and root rot in crops, especially those of lower altitude. (II) The intensity of winds greater than 180 km;h cause 2-3 times more damage than tropical storms. (III) Agricultural management determines the greater root resilience of crops. These difficulties were raised by producers of both farms in the interviews and surveys applied, they correspond to the difficulties referred to in the studies of 57 farms in Mayabeque by Fundora *et al.* (2024). These results also correspond to temperature increases above the 30-year historical average (Table 2) for 2021, which may result in lower plant biomass due to water stress and an impact on animal feed due to forage shortages.

These events modify the respiratory rate of plants and animals, photosynthesis, and the phenological development of crops and pastures. Drought determines water availability for growth, influencing evapotranspiration and water stress with humidity. All of these parameters impact biomass formation (Taiz, 2025). The authors report that water deficit is the main limiting factor for plant growth (smaller plants with fewer vigorous leaves, with possible wilting and premature senescence). Less dense and productive pastures, forage crops, and natural vegetation. Less diversity of drought-tolerant species. The nutritional quality of biomass can be affected by increasing the concentration of fibers (less digestible) and decreasing the protein and energy content in plants due to slower growth or stress. It is important to consider that in 2023, the NDVI/biomass ratio does not follow the expected trend of positive variation with the combination of factors: (I) The occurrence of climatic stress events causes in the plant, the saturation of the Leached Red Ferralitic soil and the leaching of nutrients, which reduces photosynthetic activity and lowers the NDVI, but not necessarily the accumulated biomass, especially woody ones that have a heavy structure. (II) Woody vegetation (mango, avocado, ficus) is voluminous, tall and the NDVI is low, being sensitive to chlorophyll and water stress, excessive rainfall can cause chlorosis, or leaf fall, reducing the NDVI despite the existence of a high accumulated biomass that includes non-photosynthetic structures such as roots, trunks and branches of trees that persist. (III) Persistent humidity possible interferences in satellite measurements (clouds / resolution). (IV) The use of bio-inputs such as compost influences plant metabolism and the formation of accumulated biomass and foliage.

The impact on animal manure production is also affected by climatic stress, as it is the result of the digestion of feed consumed by animals (mainly forage/plant biomass). Manure production is directly related to the amount of plant biomass available for feeding, the digestibility, and composition of the feed. If the forage has nutritional quality (diluted by rapid growth), the manure may also have less, even if the volume does not change (Elizondo, 2004).

In 2021 (dry), there will be less forage available for animals due to less fresh grass to consume. According to farm producers, this year they had to use more concentrated feed and reserves of hay and silage, which are more expensive and scarce, due to the lack of processing. Dry grass, unlike fresh grass, is digested differently than grass, resulting in a lower volume of manure production per animal due to lower dry matter consumption in bulky forage.

In 2023, according to producers, excessive rainfall caused management problems when composting, collecting and storing it, expanding it, and turning it, with increased leachate and producing poor-quality compost or fertilizers. Therefore, they did not use it efficiently. Their main challenges were feed shortages, the cost of supplements, and in 2023, they noted the management situation with excess water, as well as manure and biomass loss due to moisture. They cited the development of diseases and weeds as a significant challenge. They clarified that the number and type of animals available did not vary significantly between the years of the study.

Despite these challenges, the impact of compost application on improved crop and soil management was evident, resulting in a lesser effect due to the negative changes affecting biomass formation. Although compost was prepared using farm waste in 2023, it was at 50%, which affected the amount of feed for the animals and therefore impacted manure production (Table 4). Under these conditions, which were not yet maximized with 100% utilization of waste, the results showed a tendency toward a closed-loop waste recycling process that contributes to the farm's self-sustainability (Table 5).

Farm Self-Sustainability Analysis with Generated Biomass

With the biomass modification from 2021 to 2023, other trends were highlighted (Table 5):

I. Animal self-sufficiency improved significantly without/with the application of 50% biofeed, although gaps in the nutrient balance for potassium (K) persist.

II. The carbon (C) footprint on both farms is carbon negative, suggesting greater C sequestration in 2023 (higher SOM and biomass content).

III. In the soils, SOM increased by approximately 1% on both farms, maintaining a stable C/N ratio (12), indicating stabilized organic quality (Paneque, 2002).

IV. Waste recycling efficiency decreases due to structural factors: the type of waste at Nuestra Señora farm is approximately 40%, as it consists of woody waste from fruit and ficus pruning, which requires shredding, and the equipment for this waste is unavailable. It is suggested (INCA-Cuba, 2020) that the recycling rate of this waste is 35% lower than that of herbaceous plants such as taro and plantain at La Esperanza farm.

Manure from a larger number of animals (Nuesta Señora) causes greater losses due to runoff in open pens, while smaller numbers of animals make it easier to manage and achieve more efficient composting (La Esperanza). The scale and dispersion of manure negatively affects the levels of collection complexity. At La Esperanza, the recycling independence is 13-20% higher, which may be due to the dispersion of waste concentrated in 3 ha, while at Nuestra Señora, the distance between areas is greater (15 ha), resulting in the requirement of approximately more than 30% of the labor/days. In case studies on farms larger than 15 ha, internal waste transportation reduces efficiency by 20-40% (Altieri, 2002; FAO, 2021).

This difference in waste recycling percentage is compounded by the agronomic management carried out on each farm. At Nuestra Señora, the rotation is more complex (7 crops) where the residues remain in the field as cover (not collected); at La Esperanza, strip cropping allows for its collection. In more diversified systems, less than 15% of the residues are recycled (Altieri, 2002). This emphasizes the positive impact of applying compost obtained by producers using their own resources.

Incorporating biomass transformation into the sustainability study provides the fundamental foundation for the development of the circular bioeconomy on three levels: (I) Environmental, by providing closed nutrient cycles (waste-energy-fertilizer). (II) Social, by providing stable employment in rural areas. (III) Economic, by saving energy and generating more income from the sale of surpluses. The unregulated use of biomass can unbalance the agrosystem, depleting soils and biodiversity due to overexploitation. Understanding the endogenous potential of farm-generated waste not only ensures self-sufficiency but also allows for extraction that maintains efficient natural cycles, achieving environmental optimization through the balance of its components, risk mitigation, and agricultural resilience.

It can be summarized that the La Esperanza farm confirms a more efficient self-sufficiency model than Nuestra Señora, which is presented as viable with adjustments in waste management. This includes establishing low-cost strategies for large farms to improve waste recycling and achieve less dependence on external inputs. These include establishing technologies, logistics, and property design that require less labor, such as manual shredders for pruning (increasing efficiency by 40%) and scalable tubular sausage-shaped biodigesters. Spatial management for waste collection by establishing centralized collection points approximately every 5 hectares. Training through participatory workshops on more efficient waste management and utilization contributes to the autonomy of the farm with the largest amount of hectares to manage. According to the results, to minimize these difficulties encountered, the following actions are recommended to be prioritized within the studied farms: (I) for K deficiency, apply 0.5 t/ha of potassium ash (Canavalia), and thus take advantage of the stem residues irrigated in the fields, discarded during pruning used for animal feed, together with compost enriched with this ash; which could increase by 0.3 cmol+/kg/year (Paneque, 2002). (II) Low self-sufficiency of Phosphorus (P), the use of phosphate rock (200 kg /ha) in key crops is suggested, it can improve approximately between 5-6 ppm/year. (III) On the farms, it is suggested to establish a more efficient model in the collection, maintenance and processing of waste; where established

Integrated procedure for the sustainable management of nutrients and waste on farms in Mayabeque

The above results led to a comprehensive procedure proposed to provide practical, adaptive, and self-managed solutions for managing nutrient flows and utilizing endogenous waste on typical farms in the town of Mayabeque, contributing to the transition toward a self-sustaining circular economy in the region (Figure 1).

The first step involves conducting an agroecological study of the farm to diagnose and characterize its endogenous conditions. Its main tasks include an inventory of organic waste (identifying types, volumes, and locations of generated waste). It also includes soil and nutrient flow analysis (evaluating fertility, nutrient deficiencies, and current biogeochemical cycles). It also includes mapping available resources (infrastructure, labor, low-cost local technologies, and traditional practices).

This is complemented by information gathering through interviews and participatory workshops with farm stakeholders to gain an overview of the farm's overall potential with existing materials for possible utilization.

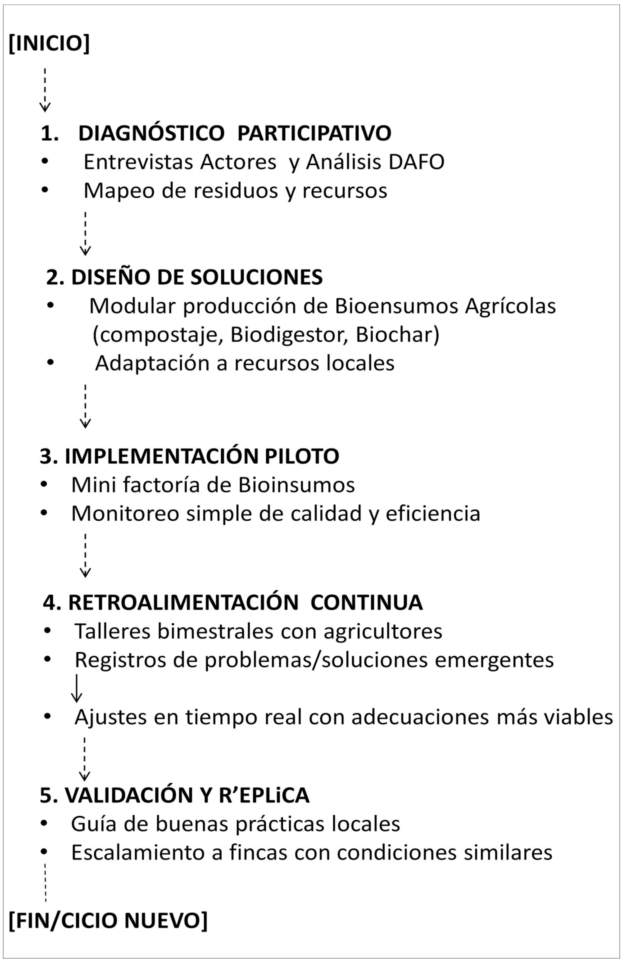

Figure 1. Diagram of the proposed feedback and adaptability procedure for nutrient and bioinput management on farms in Mayabeque.

In step 2, it is necessary to reduce the gaps in waste loss through the design of an adapted circular system. This should be based on: (I) Utilizing the largest amount and classifying waste to validate its nutritional value and ensure the nutritional quality and stability of the product; (II) Processing techniques: improved composting (introduction of protein plants in the form of ashes to improve nutritional quality, use of bioferments, vermiculture to accelerate decomposition, improvement of aeration techniques minimizing turning and creation of static piles through the use of the trunks of branches, pruning residues). Installation of small biodigesters for the production of biogas and biofertilizer, according to the capacities of waste generated in them (manure with crushed vegetable residues rich in C (straw), to reach the ideal C / N ratio of 20-30: 1) and areas of the farms. Biochar through the pyrolysis of woody residues, to improve nutrient retention in soils. Agricultural integration with the use of byproducts in cycles (manure-vegetable-compost-crops-crop residues-animal feed).

Step 3 involves participatory implementation and self-management: (I) Prioritize producer training (workshops on circular economy techniques, agroecological studies on farms primarily for their knowledge and environmental care) to achieve their active participation in the process. (II) Demonstration prototypes (model farms that implement the system to validate its effectiveness). (III) Establish flexible adaptation (according to the type and endogenous conditions of each farm (livestock, agricultural, mixed).

Step 4, Need for monitoring and systemic impact assessment based on: (I) Key indicators (reduction of unused waste, improvement of soil fertility (organic matter and NPK balance), and energy self-sufficiency (if biogas is used). (II) Continuous feedback (producer surveys to adjust the model).

Step 5, proposes the introduction of scaling and replication: (I) Develop a guide of good practices for recycling waste on farms to document the process for farms with similar conditions. (II) Implement local policies (connect with cooperatives and agricultural development programs in Mayabeque). Continuous feedback of the procedure is key to its adaptation to the current endogenous conditions on each farm. It ensures self-management based on local learning and the flexibility and scalability of the methodology.

This Improved feedback and adaptability procedures on farms should be based on: (I) Participatory diagnosis of co-construction with producers in community workshops to identify with farmers the types and quantities of waste generated; current management practices (what works and what doesn't), limitations (resources, climate, knowledge). Social mapping to locate nutrient flows and critical loss points with producers. (II) Adaptive design of the circular system, based on providing immediate solutions according to the resources of each farm: if they are small, composting and vermiculture are recommended, with livestock (biodigesters + use of biofertilizers), with excess woody biomass (biochar + mulch). Flexible porototypes testing combinations (e.g. compost + biochar) and adjusting according to results. (III) Implementation with participatory monitoring: (a) Collaborative records (shared field notebooks (producers + technicians) to document the decomposition time of residues, crop response to bioinputs, pest and disease behavior, savings in external inputs. (b) Simple indicators (% of recovered waste, cost reduction due to self-consumption of fertilizer, improvement in yields in kg/ha and soil health).

Linking the Adaptive Feedback Procedure to the Concrete Results of the La Esperanza and Nuestra Señora Farms

Table 7 lists the main problems identified on each farm, and suggests the action/estimated cost/expected impact for mitigation.

In the participatory assessment (Table 3) and biomass estimation (Table 6) (Stage 1 of the procedure), the underutilization of endogenous waste on the farms was highlighted as the main difficulty. La Esperanza has approximately 70% of its banana leaf and cow manure waste, which was underutilized, with soils that tend to acidify and have low water retention. For both farms, the assessment also revealed that more than 50% of the waste was wasted (Table 6). The solution proposed is composting banana leaves and peels, manure, and canvalia ash

Table 7. List of the main problems identified in each farm, suggesting the action/estimated cost/expected impact for their mitigation

Area	Problem	Action	Estimated Cost	Expected Impact (1-2 years)
		La Esperanza Farm		
Fertility	Potassium Deficit	Apply 500 kg/ha of plant pruning ash (protein-rich)	$ 20 USD	Increase in available potassium by 0.2 cmol+/kg
Food		Introduce canvalia to 0.5 ha of pasture (to increase forage protein)	$ 15 USD (seeds)	Increase in self-sufficiency to 95%
Waste	(-100 kg/ha in 2023)	Shred fruit tree prunings with a manual machine (to increase composting efficiency)	$ 150 USD	Recycling at 92-95%
Energy	Animal self-sufficiency could be improved	Install 5 m³ biodigesters (if all manure is to be processed)	$ 300 USD	Generate 3 m³ of biogas/day (Increase in energy self-sufficiency)
		Nuestra Señora Farm		
Fertility	Improved low-cost technology for waste processing	Apply 200 kg/ha of	$ 80 USD	Increase in P by 5 ppm, decreases N deficit by 30%
Food	Our Lady Farm	Phosphate rock + enriched compost (manure + plant matter)	$ 100 USD (seeds)	Increase in self-sufficiency to 85%
Waste/Logistics		Replace 2 ha of natural pasture with King Grass (to increase forage biomass)	$ 500 USD	Recycling at 85%
Technology	Nitrogen and Potassium Deficit	Establish 4 waste collection points (each 5 ha) with a mobile shredder	$ 600 USD	Generate 3 m³ of biogas/day (Increase in energy self-sufficiency)

(La Esperanza). In Nuestra Señora, there was an excess of mango, ficus, and avocado prunings, which were piled up and burned (nutrient loss of 200 kg/month of OM). A small biodigester technology was proposed, which was not considered by producers due to its cost and the amount of manure that would not allow for composting. Straw and/or shredded mango, avocado, and ficus prunings were added in moderate proportions (maximum 20-30% of animal manure) (maintain a C/N ratio between 25:1 and 35:1) to optimize biogas production (Table 7). This also entails the introduction of a low-cost manual shredder to reduce the size of the prunings.

In phase 3 of the pilot implementation, quantitative estimates suggest that compost production of 2 tons/year reduces the use of chemical fertilizers by 30%. Achieved improved pH and SOM adjustment from 1.8 to 3.5% for La Esperanza. Nuestra Señora was able to produce 1.5 m3/day of biogas used in cooking and fruit drying (Table 6). This stage demonstrated that these underutilized wastes can be converted into strategic resources: improved compost quality and renewable energy production.

In the fourth stage of feedback and adjustment, it was evident that La Esperanza composted slowly during the rainy season. Mobile roofing made from recycled plastic was installed, reducing composting time from 90 days to 60 days, although not by the expected amount. The type of biomass to be used could be sediment in the biodigester, which is why it is suggested to create an artisanal stone and mesh filter for use on the farm with a longer useful life for the system. These results suggested reintroducing feedback into the process in step 4, with the participation of local stakeholders and producers, once again demonstrating its importance. In stage 5 of model validation and replication, the scalability of the process for the viable utilization of endogenous waste generated on farms to achieve self-sufficiency is suggested, as is the system's adaptability to local priorities. In La Esperanza, with 80% of the waste utilized and 65% nutritional self-sufficiency, the annual savings are estimated at USD 1,200. Nuestra Señora, with 70% of the waste utilized and 50% nutritional self-sufficiency, is estimated to achieve annual savings of USD 950 (Table 7).

The analysis in Table 7 also allows for a comparison of the investment with the estimated key benefits that the proposed actions for these farms could bring. For La Esperanza, the total investment would cost approximately $485 USD, with key benefits such as closing nutrient loss gaps like K, along with increased animal feed self-sufficiency of 95%. In the case of Nuestra Señora farm, the total investment would be approximately $1,280 USD, with key benefits such as a ≈50% reduction in N and K deficits through more efficient large-scale waste management. On both farms, participatory workshops are essential for developing these self-sustaining models, primarily on topics such as the introduction of low-cost technologies that enable farm self-sustainability, such as accelerated composting with higher nutritional quality, biodigester management with the addition of plant waste with manure, and the installation of mini-biofactories for the production of bio-inputs with the efficient management of farm waste and endogenous resources.

Workshops included accelerated composting with higher nutritional quality and biodigester management with the addition of plant waste with manure.

The feedback process within the procedure allowed for flexibility without losing sight of the central objective of closing nutrient cycles with the farms' endogenous resources.

CONCLUSIONS

- The farms demonstrated that the integration of bioinputs improves self-sufficiency and reduces the carbon footprint, but require adjustments in waste recycling management and nutrient balance, primarily for potassium and phosphorus. The study quantifies the possibility of efficiently validating endogenous waste (plant and animal manure) generated on farms for bioinput production and the impact of their introduction on farm self-sufficiency for the agroecological transition of production processes.
- With the application of the proposed procedure on farms, impacts estimated to increase self-sufficiency by 92-95% within the next 1-2 years are expected, improving soil fertility by approximately increasing potassium availability by 0.2 cmol/kg, phosphorus availability by 5 ppm, and reducing nitrogen deficit by 30%. Livestock feed self-sufficiency will increase from approximately 78% to 85%; overall farm self-sufficiency is estimated at 95%.
- The estimated total investment benefits were approximately $485 USD for La Esperanza and $1,280 USD for Nuestra Señora. Animal feed self-sufficiency increased by 95% on the first farm, while on the second, N and K deficits were reduced by 50% through more efficient waste management.
- An adaptive and viable procedure was developed for typical local farms in Mayabeque.
- Local farms with a typical agricultural composition of the region can replicate successful integrated waste management models with diversity using affordable, low-cost technologies, such as biodigesters and composting, integrating waste into food and renewable energy production chains in closed loops, and monitoring the impacts to adjust the strategies outlined. The design of interconnected closed-loop nutrient flows for the reuse of endogenous farm waste maximizes self-sustainability, reduces dependence on external inputs, and promotes a circular economy within the ecological system.
- Include these models in rural development programs with incentives for the production of low-cost bio-inputs on local farms in the Mayabeque province and throughout the country with characteristics typical of those studied.

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