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Transformation Of Agro-Productive Systems Towards Sustainability: Biofertilizers, Hydroponics, Silvopastoral Systems And Water Reuse As Technological Axes

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Summary
The transformation of traditional agro-productive systems towards sustainable models is an imperative in the face of climate change, environmental degradation and food insecurity. This article explores four key technological axes—biofertilizers, hydroponics, silvopastoral systems, and water reuse—as pillars of the agroecological transition. A mixed methodological approach is adopted, with bibliographic review and case analysis. The results indicate that these technologies, when properly integrated, can increase productivity, reduce environmental impacts, and promote sustainable rural development. The findings highlight the need for public policies, technical education, and financing to drive widespread adoption.
Keywords: *sustainability, agroecology, biofertilizers, hydroponics, silvopastoral, water reuse.*

INTRODUCTION

Agro-productive sustainability has become a central issue on the global agenda, especially in the face of the challenges faced by the agricultural sector arising from climate change, the degradation of natural resources, and the growing pressure on food systems (FAO, 2021). Conventional intensive agriculture practices, although responsible for increasing production in the twentieth century, have contributed significantly to soil and water pollution, biodiversity loss, and greenhouse gas emissions (Gutiérrez et al., 2022). In this context, the design of strategies that allow a transition towards sustainable agro-productive systems is urgent and necessary.Sustainability is not only limited to reducing negative impacts, but also involves transforming agricultural processes through technological innovation, efficient management of natural resources, and climate resilience (Pérez-Rodríguez & Salazar, 2020). In particular, emerging technologies in sustainable agriculture have proven effective in meeting these challenges without sacrificing productive performance. These technologies include **biofertilizers**, which reduce dependence on synthetic fertilizers while improving soil health; **hydroponics**, which allows soilless crops and optimizes the use of water and nutrients; **silvopastoral systems**, which integrate trees, pastures and livestock in a harmonious way; and the **reuse of treated** water, which makes it possible to take advantage of residual water resources in areas with water stress (López-García et al., 2023; Rodríguez et al., 2022).These technological innovations not only represent technical solutions, but also social and economic opportunities for rural communities. Productive diversification, the generation of green employment and the valorisation of local knowledge are fundamental aspects of this transformation (Rincón & Castañeda, 2021). Similarly, the agroecological and circular approach promotes a new vision of rural development based on ecological efficiency, equity, and food sovereignty (Moreno & Ramírez, 2023).Despite the potential demonstrated by these technologies, their massive implementation still faces structural limitations: lack of effective public policies, scarce technology transfer, cultural resistance to change, and lack of financing. Therefore, it is crucial to understand the technical, economic and social elements that determine their adoption, as well as the positive impacts they can generate at different production scales.This article proposes a review and integrated analysis of four key technological axes for the transformation of agro-productive systems towards sustainability: biofertilizers, hydroponics, silvopastoral systems and water reuse. Through a mixed methodology and based on recent studies in Latin America, its advantages, limitations and articulating potential within the contemporary agroecological model are identified.

Theoretical Framework

The transformation of agro-productive systems towards sustainability implies the adoption of new practices that harmonize agricultural productivity with respect for natural cycles, soil health, biodiversity and the responsible use of water. This theoretical framework addresses four technological pillars that are being widely researched and adopted in different regions of the world: biofertilizers, hydroponics, silvopastoral systems and water reuse.

1. Biofertilizers

Biofertilizers are biological inputs made from living microorganisms that, when applied to the soil or seeds, promote the availability of nutrients and stimulate plant growth. Among the most commonly used microorganisms are rhizobacteria, mycorrhizae, and cyanobacteria (Rodríguez et al., 2022). According to Sánchez et al. (2021), biofertilizers reduce the need for chemical fertilizers by up to 50%, contributing to reducing nitrate and phosphate pollution. In addition, they promote the microbial biodiversity of the soil and improve its structure.

Table 1. Comparison between biofertilizers and chemical fertilizers

Feature	Biofertilizers	Chemical fertilizers
Origin	Biological (microorganisms)	Synthetic (industrial processes)
Environmental impact	Low	High (pollution and eutrophication)
Long-term cost	Low	High
Soil improvement	Yes (microbial life, structure)	No (you can demote it)
Application	Compatible with organic farming	Restricted use in agroecology

Source: Adapted from Rodríguez et al. (2022); Sánchez et al. (2021)

2. Hydroponics

Hydroponics is a soilless growing method in which plants grow with their roots submerged in a nutrient-rich solution. This system has become a viable alternative for production in urban areas and regions with poor or contaminated soils (López & Castillo, 2023).

One of its main advantages is the efficient use of water: it can require up to 90% less water than conventional agriculture (Morales et al., 2020). It also allows for controlled and continuous production throughout the year.

Table 2. Advantages of hydroponics compared to traditional agriculture

CRITERION	HYDROPONICS	TRADITIONAL AGRICULTURE
WATER USE	Very low	High
NEED FOR LAND	No	Yes
ENVIRONMENTAL CONTROL	High	Low
PRODUCTIVITY	Loud	Variable
SPACE REQUIREMENT	Reduced	Extensive

Source: Morales et al. (2020); López & Castillo (2023).

3. Silvopastoral systems

Silvopastoral systems integrate trees, shrubs, fodder, and animals into a productive unit, combining livestock and forestry activity in a synergistic way (Fernández & Salazar, 2020). These systems increase biodiversity, sequester carbon, and improve animal welfare by providing shade and natural food. According to Paredes et al. (2021), this model reduces soil erosion and improves soil fertility, while increasing livestock productivity. In addition, it allows diversifying income for rural producers.

Table 3. Ecological benefits of silvopastoral systems

ECOLOGICAL BENEFIT	DESCRIPTION
CARBON CAPTURE	Atmospheric CO_2 storage in tree biomass
SOIL CONSERVATION	Reduced erosion and improved water infiltration
IMPROVED MICROCLIMATE	Shade, humidity and thermal regulation for livestock
FUNCTIONAL BIODIVERSITY	Habitat for pollinators and biological controllers

Source: Fernández & Salazar (2020); Paredes et al. (2021).

4. Water reuse in agriculture

The reuse of treated wastewater in agriculture has become relevant in contexts of water scarcity, particularly in arid areas or areas with uncontrolled urban growth. This practice makes it possible to close the water cycle and take advantage of the nutrients present in the wastewater (Martínez-López et al., 2023).

Various studies have shown that the use of treated grey and black water not only reduces pressure on conventional water sources, but can also improve soil fertility when managed safely (Jiménez et al., 2021).

Table 4. Risks and benefits of reusing treated water in agriculture

Evaluated aspect	***Advantages***	***Risks (if there is no control)***
Water availability	Increases water supply	Contamination if not treated correctly
Nutritional content	Provides nitrogen and phosphorus	Excess salts and heavy metals
Cost reduction	Savings on fertilizers and irrigation	Initial costs in infrastructure
Sustainability	Closing cycles and circular economy	Social rejection due to ignorance

Source: Martínez-López et al. (2023); Jiménez et al. (2021).

METHODOLOGY

This study adopted a **mixed methodological approach of descriptive and analytical type**, aimed at exploring the role of four key technologies in the transition of agroproductive systems towards sustainable models. The methodology combined systematic documentary review, comparative case analysis, and application of qualitative sustainability matrices, in accordance with approaches proposed by Díaz-García and Pérez (2020).

1. Research Design

A cross-sectional non-experimental design **was used**, focused on the identification and comparison of good agroecological technological practices in Latin America during the period 2019–2024. The research was structured in three phases:

1. **Systematic documentary review**
2. **Case Studies**
3. **Impact assessment using a multi-criteria matrix**

The integration of qualitative and quantitative techniques allowed for an exploratory and explanatory multivariate analysis (Ramos & Tejada, 2022).

2. Systematic documentary review

More than 50 primary sources **were consulted** , including academic articles, technical reports from international organizations (FAO, ECLAC, UN Water), and master's theses. The inclusion criteria were:

- Publications between **2019 and 2024**
- Studies with a focus on **biofertilizers, hydroponics, silvopastoralism** and **water reuse**
- Verifiable or replicable results
- Peer Review

The Zotero bibliographic manager and databases such as **Scopus, Redalyc and Google Scholar** were used. The search strategy included descriptors such as: "sustainable agriculture", "green technologies", "bio-inputs", "water cycle" and "agroecological resilience".

3. Case analysis

Four flagship case studies **were selected**, one for each technology axis, based on their local impact and the availability of quantitative information. The selection was made according to the following criteria:

- **Geographical location**: projects in Latin America
- **Productive scale**: small and medium-sized rural farms
- **Data availability**: comparable results in productivity, efficiency, costs, etc.

The cases were systematized through technical files and secondary structured interviews taken from institutional reports and open-access databases (Paredes & López, 2021).

4. Evaluation by sustainability matrix

A multi-criteria evaluation matrix was applied to measure the impact of each technology in three dimensions: **environmental, economic and social**. The model proposed by Moreno et al. (2020) was adapted, assigning scores from 1 to 5 to each indicator according to the level of contribution to sustainable development.

Table 5. Sustainability Assessment Matrix by Applied Technology

Technology	Environmental Dimension	Economic Dimension	Social Dimension	Sustainability Average
Biofertilizers	5 (high)	4 (media-alta)	4 (media-alta)	4.3
Hydroponics	4 (media-alta)	5 (high)	3 (average)	4.0
Silvo pastor	5 (high)	4 (media-alta)	5 (high)	4.7
Water reuse	4 (media-alta)	4 (media-alta)	3 (average)	3.7

Source: Authors' elaboration based on Moreno et al. (2020) and data from the cases analyzed.

5. Validation and triangulation

To guarantee **internal validity**, methodological triangulation was applied between the bibliographic sources, the data extracted from the cases and the criteria established in the matrix. Reliability was reinforced by cross-review between two researchers and the use of auditable spreadsheets (Delgado & Romero, 2021).

RESULTS

The analysis of the selected technologies—biofertilizers, hydroponics, silvopastoral systems, and water reuse—showed significant impacts on environmental sustainability, productive yield, and economic viability in various agroecological contexts in Latin America. The results are presented below organized by technological axis, integrating figures obtained from the selected case studies and secondary sources reviewed.

**1. Biofertilizers: impact on s
oil productivity and quality**

On coffee farms in Chiapas, Mexico, the application of microbial biofertilizers increased crop yield by **28.6%** compared to conventional management, while soil microbial activity doubled over an 8-month period (Rodríguez et al., 2022). In addition, a **40% reduction** in the use of chemical fertilizers was observed, which implied an improvement in the ecological balance of the agroecosystem.

Table 6. Results of the application of biofertilizers in coffee cultivation (2022)

Indicator	Conventional handling	Applied biofertilizer
Yield (kg/ha)	1.200	1.545
Soil pH	5.2	6.3
Microbial activity (CFU/g)	$1{,}1\times10^6$	2.4×10^6
Cost per fertilization (USD/ha)	360	216

Source: Rodríguez et al. (2022).

2. Hydroponics: water efficiency and productivity

In a lettuce hydroponic system installed in Bogotá (Colombia), a yield of **15 kg/m²/cycle was reported**, compared to **7.2 kg/m²/cycle** in traditional soil cultivation, with a reduction of up to 88% in water consumption (López & Castillo, 2023). In addition, the harvest time was shortened by an average of 7 days.

Table 7. Comparison between traditional cultivation and hydroponic lettuce system

Indicator	***Soil Cultivation***	***Hydroponic system***
Production per m² (kg)	7,2	15
Harvest cycle (days)	45	38
Water consumption per cycle (L/m²)	75	9
Use of agrochemicals	Middle	Low

Source: López & Castillo (2023).

3. Silvopastoral systems: livestock productivity and ecological restoration
In Valle del Cauca (Colombia), the adoption of silvopastoral systems showed a **35%** increase in milk production per hectare, an improvement in the body mass index of cattle (+15%), and a 40% recovery of native vegetation cover in three years (Salazar et al., 2021).

Table 8. Results of the silvopastoral system compared to the conventional system

Indicator	Conventional livestock farming	Silvopastoral system
Milk production (L/ha/month)	900	1.215
Weight gain (kg/animal/month)	18	24
Available shade (%)	10	65
Vegetation cover (%)	25	65

Source: Salazar et al. (2021).

4. Reuse of treated water: irrigation efficiency and nutrient savings
In an agricultural project in Lima, Peru, the reuse of treated greywater irrigated 2.5 hectares of vegetables, with a **35% reduction** in fertiliser expenditure thanks to the nutrients present in the water (Martínez-López et al., 2023). Likewise, the consumption of drinking water for irrigation was reduced by **70%.**

Table 9. Results of the use of treated water in vegetable irrigation

Indicator	***Drinking water***	***Treated wastewater***
Monthly water consumption (m³/ha)	110	33
Monthly cost per fertilization (USD)	140	90
Nitrates supplied (mg/L)	3,2	12,5
Farmers' opinion (scale 1–5)	2,7	4,3

Source: Martínez-López et al. (2023).

GENERAL SYNTHESIS OF COMPARATIVE IMPACTS

Table 10. Comparative impacts of the technologies evaluated

Technology	Productive increase (%)	Reduction of inputs (%)	Outstanding environmental improvement
Biofertilizers	25–30	40–50	Microbial activity, soil fertility
Hydroponics	100+	70–90 (water)	Water efficiency, absence of soils
Silvo pastor	30–40	20 (medications)	Vegetation cover, biodiversity
Water reuse	0–10	35 (fertilizers)	Water saving, nutrient recovery

Source: Authors' elaboration based on primary and secondary data (2019–2024).

CONCLUSIONS
The transformation of agro-productive systems towards sustainable models is a complex but urgent process, driven by the need to reduce the negative impacts of conventional agriculture, adapt to climate change and ensure long-term food security. The results of this research allow us to affirm that the integration of technologies such as **biofertilizers**, **hydroponics**, **silvopastoral systems** and the **reuse of treated water** represents a viable and necessary alternative to achieve these objectives in the Latin American context.First, biofertilizers were found to significantly improve soil health, increase microbial biodiversity, and reduce dependence on chemical inputs, which directly contributes to the restoration of degraded agroecosystems (Rodríguez et al., 2022). In addition, this technology is economically accessible to smallholders, making it easier to adopt in vulnerable rural communities (Sánchez et al., 2021).

Hydroponics proved to be a highly efficient solution in urban and peri-urban contexts, allowing the intensive cultivation of vegetables with low water consumption and without the need for fertile soils. This technology has enormous potential to contribute to urban food sovereignty, especially in scenarios of water scarcity or soil degradation (López & Castillo, 2023; Morales et al., 2020). Regarding **silvopastoral systems**, positive impacts were identified both on livestock productivity and on the ecological regeneration of rural landscapes. These systems increase land-use efficiency, promote biodiversity conservation, and reduce greenhouse gas emissions by integrating trees into livestock production (Salazar et al., 2021; Paredes & López, 2021). In addition, they strengthen the climate resilience of rural communities by diversifying livelihoods.The **reuse of treated wastewater** also emerges as a promising strategy for sustainable agriculture, especially in urban or semi-arid areas. Its application not only reduces pressure on drinking water sources, but also provides nutrients to the soil, thus reducing fertilization costs (Martínez-López et al., 2023; Jiménez et al., 2021). However, it requires adequate treatment processes, constant monitoring, and social acceptance for its safe and effective implementation.In a cross-cutting way, the results indicate that these technologies should not be understood as isolated solutions, but as **articulating axes of an integrative agroecological model**, which requires the strengthening of local capacities, access to green financing, inclusive public policies, and greater investment in applied research (Moreno & Ramírez, 2023). Likewise, technical education and community participation are indispensable conditions for the adoption and sustainability of these innovations.

In conclusion, moving towards sustainable agro-productive systems is not only desirable, but essential. The synergistic adoption of biofertilizers, hydroponics, silvopastoral systems, and water reuse offers a viable path to achieve a more productive, just, and ecologically balanced agriculture. Future research should focus on the development of integrated, scalable and adaptable models to diverse territorial realities.

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