Sustainability and smart agriculture

on agrivoltaic and off-grid systems in Israel as a model for the andean region of Ecuador

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DOI: 10.61854/rccedia.v1n1.001
Sent: February 11, 2026
Approved: April 27, 2026
Published: Tuesday, July 14, 2026

Abstract

The global climate crisis and increasing competition for land use demand an integrated management of the water-energy-food (WEF) nexus. This study analyzes the integration of Information and Communication Technologies (ICTs) and agrivoltaic (Agri-PV) systems in Israel as a resilience model for the high Andean region of Ecuador. The primary objective was to evaluate the technical efficiency of dual land use and decentralized (off-grid) technologies using standardized indicators such as the Land Equivalent Ratio (LER) and Water Use Efficiency (WUE). The methodology involved a transdisciplinary case study across six strategic analysis units (Arava Valley, Ramat Negev, Ma'ale Gilboa, among others) utilizing IoT instrumentation and precision sensors for microclimate and productivity monitoring. Results demonstrate that agrivoltaics can achieve LER values of up to 1.99, reducing ambient temperatures by 3.00 °C and improving WUE between 20.00 % and 47.00 %. Although a 19,40% reduction in gross yield was reported for certain crops, the annual net profit was 9.54 times higher than the conventional model due to distributed energy generation. The study concludes that the innovations observed in Israel offer a viable roadmap for the Ecuadorian highlands, enabling frost mitigation, erosion reduction, and the strengthening of energy sovereignty in rural communities.

Keywords:
agriculture 4.0, technology,
information, communication,

Introduction

The global climate crisis has driven a radical transformation in natural resource management, placing sustainability and smart agriculture at the center of development policies to ensure productivity and resilience. In this context, the water-energy-food (WEF) Nexus is characterized by a fragile balance in which competition for land use has intensified dramatically (Chopdar et al., 2024; Zainali et al., 2025). The central challenge lies in the technical incompatibility of isolated production models, whereby the expansion of photovoltaic infrastructure, whose global installed capacity exceeded 14 GWp in 2021, frequently displaces agricultural production from high-quality farmland (Sollazzo et al., 2025; Widmer et al., 2024). Information and communication technologies (ICT) act as the driving force of Agriculture 4.0 by integrating IoT sensors, artificial intelligence, and connectivity protocols to maximize efficiency under resource-scarce conditions (Díaz et al., 2025; Pathmudi et al., 2023).

Israel, through its innovation model based on kibbutzim and R&D centers, has validated the agrivoltaic (Agri-PV) paradigm as a systemic solution that proposes the vertical coexistence of photovoltaic modules and crops (Ben Naim et al., 2025; Zohar et al., 2022), thereby resolving the land-use conflict between energy generation and food production (Schindele et al., 2020; Widmer et al., 2024; Sollazzo et al., 2025; De Francesco et al., 2025; Cosme et al., 2025). By using elevated solar panels, a synergistic effect is achieved in which plants benefit from partial shading, while the panels operate at lower temperatures due to plant transpiration (Ben Naim et al., 2025). This technology is particularly relevant for the Ecuadorian highlands, where intense solar radiation and nighttime frost require climate protection systems (CELEC EP, 2024).

The fundamental indicator in agrivoltaics is the Land Equivalent Ratio (LER), which quantifies the efficiency of producing energy and food simultaneously compared with separate production systems (Schindele et al., 2020). An LER > 1.0 indicates a dual land-use advantage. Recent studies demonstrate that total land productivity can increase by up to 60%, corresponding to an LER of 1.6 (NREL, 2023). In the Andean-Amazon transition region of Peru, studies published in 2025 reported that semitransparent configurations achieved the highest efficiency values, with an LER ranging from 1.95 to 1.99, followed by bifacial systems (1.66 to 1.90) and monofacial systems (1.51 to 1.72). These findings indicate that, in tropical mountain ecosystems, the response of the agricultural system is the primary driver of LER variability rather than energy generation itself.

Unlike conventional solar farms, Agri-PV systems function as active microclimate modifiers. The scientific literature highlights the mutual cooling effect: crop transpiration reduces local air temperature, cooling the solar panels by between 8.9°C and 10.0°C, which can increase power generation efficiency by up to 3.0% (Zainali et al., 2025). Simultaneously, the projected shade reduces soil temperature by between 3°C and 4°C and

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ambient temperature by approximately 1 to 4°C.

The physiological response is highly species- and system-specific. In sweet potato (Ipomoea batatas) cultivated under spectrum-splitting systems, a 31% reduction in evapotranspiration and a 56% increase in fresh biomass have been documented (Omer et al., 2024). In contrast, for heliophilous species such as maize and wheat, excessive panel density (PCR > 0.40) may significantly reduce yields, as observed in the U.S. Midwest, where maize and soybean yields decreased by 24% and 16%, respectively, under humid conditions (Jia et al., 2026). However, in semiarid regions, shading alleviates water stress, allowing soybean yields to increase by up to 6% (Mehta & Zörner, 2025).

Within the WEF Nexus framework, agrivoltaics improves water use efficiency (WUE) by between 20% and 47% (Zainali et al., 2025). In Spain, integrating Agri-PV with regulated deficit irrigation (RDI) reduced water consumption in tomato cultivation by 50%, while maintaining competitive water productivity despite a 20% reduction in gross yield (Omer et al., 2024).

Water resilience is further strengthened through decentralized systems. The Laguna Innovation technology, validated in Israel, enables wastewater treatment using Vertical Green Walls, operating entirely autonomously with solar power and remote IoT monitoring (Arava Institute, 2024; Aviram et al., 2025). Other advances include atmospheric water generation (WaterGen) and ultrafiltration (NUF technology), which operates by gravity without chemicals, benefiting vulnerable communities in Panama and Israel (Arava Institute, 2024; Embassy of Israel, 2025).

Although the installation cost of Agri-PV systems is between 4% and 115% higher than that of standard photovoltaic systems due to elevated support structures of up to 5 meters that allow agricultural machinery to pass beneath them (Sadeghi Chamazkoti et al., 2025), income diversification compensates for this investment. Cost-benefit analysis of off-grid solar pumping systems shows a benefit-cost ratio of 9.3 compared with 8.4 for grid-connected systems, with investment payback periods reduced to between 3 and 6 years in diesel replacement scenarios (Herlina et al., 2025).

At the policy level, Israel reached a milestone in February 2026 by approving the first national land-use plan dedicated exclusively to Agri-PV, establishing a clear regulatory framework for large-scale pilot projects. This governance framework is essential for reducing the financial risk faced by smallholder farmers and promoting social acceptance (SolarQuarter, 2026).

The Ecuadorian Highlands possess strong solar potential (2.8 to 6.4 kWh/m²/day) but suffer from catastrophic soil degradation, with erosion rates exceeding natural soil formation by 9 to 286 times. Agri-PV in the Andes would not only generate clean energy for pressurized irrigation systems, whose adoption rate is only 20%, but would also serve as a protective barrier against frost and extreme precipitation events that accelerate erosion on slopes of up to 70%. Studies conducted in Cuenca and Azogues confirm that crops such as lettuce achieve high yields under partial shade, allowing a 66% increase in market price due to improved quality (Oñate-Valdivieso et al., 2024).

The relevance of this study lies in the transfer of these models to the Ecuadorian high-Andean region. The implementation of Agri-PV systems represents an opportunity for three-dimensional sustainability: environmental, by mitigating frost and reducing evapotranspiration; economic, by diversifying income through the sale of surplus electricity; and social, by strengthening the sovereignty of disconnected rural communities (Alai Secure, 2025; Coherent Market Insights, 2025).

The objectives of this study focus on evaluating the technical efficiency of Agri-PV systems and decentralized (off-grid) technologies observed in Israel, using the Land Equivalent Ratio (LER) and Water Use Efficiency (WUE) as key performance indicators. In addition, the study seeks to analyze the impact of ICT-assisted microclimate management on the physiology of sensitive crops to mitigate thermal stress and, finally, to establish a sustainability roadmap integrating the environmental, economic, and social pillars for the implementation of pilot projects in Ecuador's Inter-Andean Valley.

Methods

The methodology employed in this study is an analytical review with a descriptive case study, based on the author's technology transfer experience and the synthesis of specialized technical literature. The study adopts a transdisciplinary approach to evaluate the water-energy-food (WEF) Nexus, prioritizing the distinction between verifiable scientific evidence and descriptive observations (Zohar et al., 2022). Primary data collection was conducted during a technical immersion in Israel between November and December 2025, with an emphasis on the infrastructure supporting Agriculture 4.0.

Study sites and units of analysis

To ensure the traceability of the study, the exact geographic coordinates of the units of analysis were identified based on their representativeness within the Israeli innovation ecosystem. The sites are distributed across diverse climatic zones, ranging from the extreme aridity of the south to the elevated regions of the north:

- Arava Institute for Environmental Studies (Ketura): Located in Kibbutz Ketura, Arava Valley (29°58′3.36″N, 35°4′15.24″E). This center leads research on fixed and mobile agrivoltaic systems under hyper-arid conditions.
- Ma'ale Gilboa Wind Farm and Energy Storage Facility: Located at the summit of Mount Gilboa, northeast of the Samaria mountain range (32°28′35″N, 35°25′13″E). The specific wind farm is located at 32°28'1.6"N, 35°25'36.3"E, serving as a model for energy flexibility and pumped-storage energy systems.
- Yoel De Malach Center (Ramat Negev): Agricultural research station located near Kibbutz Revivim (approximately 31°02'33"N, 34°43'15"E). It specializes in crop responses to salinity and desert thermal stress.
- Al-Furaa Resilience Hub: Located in the unrecognized Bedouin village of Al-Furaa, near the Beersheba-Arad highway in the central Negev. It serves as the pilot site for decentralized off-grid water and energy technologies.
- Ashalim Solar Thermal Power Station: Located in the Negev Desert, near the community of Ashalim (30°57′45″N, 34°43′48″E). It was evaluated as a benchmark for large-scale energy infrastructure.

Definition and operationalization of variables

The fundamental metric variables used to measure the sustainability of the water-energy-food Nexus were conceptually and operationally defined. First, the Land Equivalent Ratio (LER) was defined as an indicator of dual land-use efficiency, as shown in Equation 1 (TrinaSolar, 2025; Willockx et al., 2020).

$$LER = \frac{Y_{cultivo,AV}}{Y_{cultivo,FS}} + \frac{E_{AV}}{E_{FS}} \quad \text{(Ec. 1)}$$

The LER is operationalized as the sum of the relative agricultural and energy yields. Specifically, Ycultivo refers to crop productivity under the agrivoltaic structure (AV) and under full sunlight

(FS), whereas E represents agrivoltaic energy production (AV) and the energy generation of a standard photovoltaic system without crops beneath the panels (PV).

Another variable used in this study is Water Use Efficiency (WUE), defined as the ratio between the total biomass produced and the volume of water consumed (kg/m³), measured using electronic flow meters and soil moisture sensors (Zainali et al., 2025).

Finally, Photosynthetically Active Radiation (PAR) was considered, defined as the amount of light available for photosynthesis within the 400 to 700 nm spectrum, measured beneath photovoltaic panels in μmol/m²/s (Ben Naim et al., 2025; Cosme & Vázquez and Parraguirre, 2025).

Instrumentation and data collection techniques

The study was initially based on visits to sites of interest in Israel where the use of advanced monitoring tools integrated through the Internet of Things (IoT) was observed. Sensor networks were examined for the continuous measurement of volumetric soil moisture, ambient and soil temperature, and nutrient levels such as carbon and nitrogen (Santos Valle & Kienzle, 2021).

Structural parameters were recorded, including the Ground Coverage Ratio (GCR), the module height standardized at 5 meters to allow the passage of agricultural machinery, and the spacing between rows (Willockx et al., 2020). Finally, data obtained from real-time monitoring platforms were analyzed to evaluate the quality of reclaimed water in Laguna Innovation treatment systems and the atmospheric water production of WaterGen (Arava Institute, 2024).

Analysis and validation procedures

The technical analysis procedures focused on evaluating agricultural performance under different photovoltaic shading configurations and the efficiency of decentralized systems. Productivity data for tomato and zucchini (Cucurbita pepo) were specifically examined by evaluating fresh and dry biomass parameters, as well as postharvest quality (Omer et al., 2024; Rouini et al., 2025). The validation of the primary information was carried out through data triangulation with previous research led by Dr. Tali Zohar and Dr. Clive Lipchin (Ben Naim et al., 2025; Zohar et al., 2022).

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Results

The findings of this study are derived from the direct observation of operational infrastructure and the analysis of data collected within Israel's innovation ecosystem. The results demonstrate that the integration of information and communication technologies (ICT) enables granular management of the water-energy-food (WEF) Nexus, optimizing productivity in extremely arid environments. The application of these technologies in the Ecuadorian highlands has the potential to positively impact food sovereignty, environmental sustainability, and the energy independence of rural and urban communities

Precision Agriculture, Robotics, and the Coupled Design Principle

In Israel, interest in agrivoltaics has moved beyond the experimental stage to become integrated with national climate adaptation strategies. The collected evidence reinforces the agronomic-energy coupled design principle, which states that system configuration must be tailored to each specific crop. It was determined that parameters such as module height (standardized at 1.70 m in low-height trials and 5.00 m to allow the passage of agricultural machinery), panel density, and the use of bifacial technologies are critical determinants of system success (Cosme & Vázquez and Parraguirre, 2025; Sollazzo et al., 2025).

ICT is the critical enabler of agricultural sustainability under hyper-arid conditions. Figure 1 presents a technical composition of the observed systems. It highlights the use of autonomous agricultural robots powered by bifacial solar panels to perform multipoint monitoring of critical variables, including volumetric soil moisture, nitrogen concentration, and soil organic carbon. This data stream enables the system to deliver the exact amount of water and fertilizer through computerized fertigation, eliminating input waste under conditions of resource scarcity (Santos Valle & Kienzle, 2021).

Off-Grid Systems for Wastewater Treatment

Within the context of smart and decentralized agriculture, Laguna Innovation technology represents a paradigm shift in wastewater treatment for irrigation. The Vertical Green Wall (VGW-BF) system, operated entirely off-grid using solar panels, integrates IoT sensors that transmit 24/7 data on effluent quality and operational status (Figure 2).

At the Al-Furaa Regional School, which serves 1,200 students, this modular infrastructure enables the recovery of nutrient-rich effluents for local agricultural irrigation. Operational data indicate contaminant removal efficiencies exceeding 90.00% for biochemical oxygen demand (BOD□) and total suspended solids (TSS), while eliminating sludge production and drastically reducing the energy footprint compared with centralized sanitation networks (Arava Institute, 2024; Aviram et al., 2025).

Figure 1

Technical composition of Agriculture 4.0 and agrivoltaic systems: (A) autonomous robot for precision irrigation and nutrient (C, N) monitoring under bifacial structures; (B) technical view of the inclination of sun-tracking modules for optimizing photosynthetically active radiation (PAR).

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Figure 2

Configuration of the Laguna Innovation VGW-BF wastewater treatment system

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The research conducted in the Arava Valley and Ma’ale Gilboa provides quantitative evidence of the ability of Agri-PV systems to positively modify the microclimate. It was observed that intelligent shading management reduced ambient temperature beneath the panels by an average of 3.00°C, creating a thermal refuge for crops.

For sweet potato (Ipomoea batatas), Omer et al. (2024) reported a 31.00% reduction in evapotranspiration and a remarkable 56.13% increase in fresh biomass under spectrum-splitting agrivoltaic configurations compared with the full-sun control. In contrast, for zucchini (Cucurbita pepo), experimental results at the Arava Institute showed no statistically significant differences in yield between shaded and full-sun plots, suggesting that the species tolerates high levels of shading without yield penalties, thereby allowing full energy generation within the same area.

Regarding dual productivity, the study by Ben Naim et al. (2025) on tomato cultivation is particularly noteworthy. Using a single-axis tracking configuration, a module height of 1.70 m, and a ground coverage ratio (GCR) of 26.00%, the authors evaluated arrangements of 5, 6, and 7 crop rows between the panels. Although the highest-density configuration (7 rows) resulted in a 19.40% reduction in gross agricultural yield due to decreased cumulative light availability, the system generated approximately 29 000 kWh per 1 000 m² per growing season.

Despite the lower harvested biomass, the annual net profit was 9.54 times higher than that of conventional agriculture. This is explained by the fact that revenues from electricity sales and savings in water-related operating costs more than compensated for the value of the lost harvest, validating the economic profitability of the model.

Water as a catalyst for peace and regional stability

In Palestinian villages, ongoing projects led by Dr. Clive Lipchin promote Israeli innovations to desalinate water from deep wells, as shown in Figure 3, which is subsequently used to irrigate date palm plantations. The provision of drinking water and solar-powered cooling solutions for postharvest preservation has not only strengthened food sovereignty but has also reinforced cross-border cooperation agreements, demonstrating that water-energy Nexus security is a prerequisite for lasting peace in the region (Arava Institute, 2025). Evidence of this is the enduring peace between Israel and Jordan, which has been sustained through the provision of drinking water enabled by Israeli desalination innovation.

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Figure 3

Al Auja Palestinian village: water-based scientific diplomacy projects

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Discussion

The evidence collected at Ma'ale Gilboa and the Arava Institute highlights that the success of smart agriculture depends on robust technological governance and the capacity to transfer knowledge to local producers. The kibbutz model in Israel has demonstrated that shared learning and the collective distribution of financial risk are critical prerequisites for the adoption of information and communication technologies (ICT) (Zohar et al., 2022). This middle-out innovation structure is particularly relevant for Ecuador, where the Andean agricultural system requires similar associative models to make the high initial investment required by Agri-PV systems feasible (Serrano et al., 2024; Zohar et al., 2022).

Reflections on land use efficiency and productivity

The findings of this study are consistent with the global trend of Land Equivalent Ratio (LER) values consistently exceeding 1.00. Whereas the study by Ben Naim et al. (2025) in Israel reported LER values ranging from 1.10 to 1.24 for tomatoes under solar tracking configurations, studies conducted in the Andean-Amazon transition region of Peru have reported significantly higher LER values, reaching up to 1.99 through the use of semitransparent panels (Gosgot et al., 2026). This discrepancy suggests that, in tropical mountain ecosystems with high diffuse solar radiation, the benefits of radiative protection are greater than those observed in mid-latitude deserts, implying the potential for nearly double the efficiency in Ecuador's Inter-Andean Valley (Gosgot et al., 2026; Serrano et al., 2024).

The results obtained in Israel present interesting contrasts with those reported under other climatic conditions. The 19.40% yield reduction in tomato reported by Ben Naim et al. (2025) is comparable to the 20.00% reduction observed in Spain under regulated deficit irrigation conditions (R. C. M., 2026). However, these findings differ markedly from those obtained in semiarid regions of Tanzania, where crops such as common bean and Swiss chard increased their yields by 123.70% and 90.30%, respectively, under agrivoltaic shading (Willockx et al., 2020). These variations confirm that Agri-PV functions as a thermal stress buffer; in regions experiencing critical temperatures, shading is not a productivity penalty but rather a productivity enhancer (Jia et al., 2026; Zainali et al., 2025).

The relationship between water, energy, food, and sustainability

From an environmental perspective, the 3.00°C reduction in ambient temperature observed in the Arava Valley is consistent with measurements reported in Arizona, where crop evapotranspiration reduced panel temperatures by up to 8.90°C (Zainali et al., 2025). This synergy improves Water Use Efficiency (WUE) by between 20.00% and 47.00% (Zainali et al., 2025), a factor of critical importance for the Ecuadorian Andes, where irregular rainfall threatens food sovereignty.

From an economic perspective, the apparent contradiction between biomass losses and the increase in net profit—up to 9.54 times higher in Israel—is explained by income diversification. This phenomenon has also been confirmed in Botswana, where Agri-PV integration reduced the investment payback period from 17 to only 4 years by replacing fossil fuels with solar self-generation (National Renewable Energy Laboratory, 2023). In Ecuador, the benefit-cost ratio of off-grid solar pumping systems is estimated at 9.30, exceeding the value of 8.40 for grid-connected systems, thereby confirming the financial viability of decoupling rural agriculture from Ecuador's unstable electrical grid (Herlina et al., 2025).

The social impact is evidenced by the Al-Furaa Resilience Hub. The implementation of ICT in disconnected communities not only provides water and energy but also serves as a scientific diplomacy tool that reduces geopolitical tensions (Aviram et al., 2025). For the Andean region, the primary social challenge lies in closing the digital skills gap. Agriculture 4.0 should not replace farmers but rather equip them with Decision Support Systems (DSS) that integrate traditional knowledge with real-time data analytics (Balamurali et al., 2025; Zohar et al., 2022).

Limitations and Scope of the Study

Despite the demonstrated advantages, this study acknowledges important limitations. High capital expenditures (CAPEX) remain the principal barrier, with installation costs increasing by as much as 115.00% compared with conventional photovoltaic systems (Sadeghi Chamazkoti et al., 2025). Crop response is highly species-specific, and the absence of a clear regulatory framework in Ecuador governing dual land use and surplus electricity injection into the power grid limits immediate commercial scalability (Serrano et al., 2024). Future studies should focus on life cycle assessments (LCA) to quantify the net reduction in the carbon footprint associated with the production of Andean vegetable crops under this model.

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Conclusions

This study demonstrates that information and communication technologies (ICT) constitute the operational core of agricultural sustainability in arid environments by integrating measurement, control, and analytics systems with critical water and energy infrastructure. The scientific evidence analyzed confirms that the agrivoltaic paradigm overcomes land-use competition by consistently achieving Land Equivalent Ratio (LER) values greater than 1.00. Under optimized configurations, such as those observed in Israel and validated in the Andean region of Peru, dual land use can increase total land productivity by up to 99.00%, positioning this technology as a systemic solution for food and energy security in the twenty-first century.

Intelligent microclimate management beneath photovoltaic modules functions as an essential thermal buffer. The reduction in ambient and soil temperatures, together with improvements in Water Use Efficiency (WUE) ranging from 20.00% to 47.00%, transforms the crop environment into a climate-resilient refuge against heat waves and prolonged droughts. These benefits are particularly critical for Ecuador's Inter-Andean Valley, where agrivoltaic systems provide physical protection against extreme UV radiation and nighttime frost while also mitigating catastrophic erosion rates that currently exceed natural soil formation by factors of up to 286.

This study reveals that income diversification through electricity generation enhances the financial viability of the model. Although Agri-PV may result in moderate yield reductions for certain crops, annual net profit can be up to 9.54 times higher than that of conventional agriculture due to electricity sales and reduced irrigation operating costs. For high-Andean communities, the implementation of decentralized systems with investment payback periods ranging from 3 to 6 years represents an opportunity to decouple rural productivity from an often unstable electrical grid.

The Israeli innovation model based on kibbutzim and community resilience hubs such as Al-Furaa demonstrates that technology should serve as a catalyst for stability and local sovereignty. Successful transfer to Ecuador requires closing the digital skills gap and strengthening governance frameworks that facilitate access to climate financing. It is imperative that academia and the public sector promote policies supporting distributed generation and dual land use, ensuring that the transition toward a resilient rural bioeconomy protects natural resources while maximizing the well-being of farming families.

Acknowledgements

The author gratefully acknowledges the MASHAV cooperation program of the State of Israel for providing mobility opportunities that enabled researchers to experience emerging technologies firsthand. The author also thanks the Arava Institute for Environmental Studies for organizing the on-site and field sessions, optimizing resources for an extended learning experience on science, technology, society, and culture within the course “Energy Transition and Innovation for Climate Adaptation,” held from November 23 to December 10, 2025.

Conflict of interest statement

The author declares that there are no conflicts of interest.

Funding sources

This article was prepared using funding from the MASHAV program of Israel and the author’s personal financial resources. This work was carried out within the framework of research project DIPI-049 of the Escuela Superior Politécnica de Chimborazo and has contributed to innovation project DIETT-INN-002-2025.

Declaration on the use of artificial intelligence

This manuscript was prepared with limited support from generative artificial intelligence (AI) tools, specifically ChatGPT, for editorial assistance tasks. All technical information, reported quantitative values, and interpretation of the findings originate from the cited primary sources or from the author’s direct observations within the framework of the case study. The author reviewed and validated all content generated with AI support and assumes full responsibility for compliance with the journal’s editorial and citation policies.

Author contributions (CRediT)

Rafael Alexander Córdova Uvidia: Conceptualization; methodology; formal analysis; investigation; resources; data curation; writing – original draft; writing.

Roberto Francisco Arias-Hinojosa: Technical support; review and editing; original draft analysis; funding acquisition for the ESPOCH-DIETT-INN-002 project.

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