14th Annual International Conference on Industrial Engineering and Operations Management
Dubai, United Arab Emirates (UAE), February 12-14, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/AN14.20240167
Published: February 12, 2024

Enhancing Agricultural Productivity and Sustainability through Technological Innovation in Latin America

Andy R. Tineo
Department of Industrial and Systems Engineering
Pontificia Universidad Católica Madre y Maestra
Santiago 51000, Dominican Republic
andytineocruz@gmail.com

Almanzor E. Vila
Department of Industrial and Systems Engineering
Pontificia Universidad Católica Madre y Maestra
Santiago 51000, Dominican Republic
almanzorvila@gmail.com

Dr. Richard Olawoyin
Department of Industrial and Systems Engineering
School of Engineering and Computer Science
Oakland University
Rochester, MI 48309, USA
olawoyin@oakland.edu

Abstract

Integration of technology in the agricultural sector in Latin American and Caribbean countries is complex, with the Dominican Republic (DR) serving as an exemplary scenario for significant findings. Key areas of study included forecasting, mechanization, infrastructure, and energy, emphasizing potential benefits in productivity, sustainability, and resilience. This study explores technological interventions in agriculture. A total of nine technology readiness levels (TRL_{1-9}) were identified, divided into TRL_{1-3} development stages, TRL_{4-6} near-real operational stages, and TRL_{7-9}, full scale readiness. Integrated site evaluation of various agricultural practices in collaboration with local agriculturist provided data for calculating the binary probability distribution of outcomes $P(TRL_i)$, and uncertainty (U) was estimated as a linear model combination of the cumulative distribution function values (CDF_j) for each TRL_i. A random deviate (r) generated from a uniform distribution (0,1) and linear interpolation was used to simulate the TRL for each technology assessed in this study. Results show that irrigation systems face resistance (TRL_5), hydroponic plantations show promise but lack cost efficiency (TRL_6), genetically modified crops demonstrate long-standing acceptance (TRL_9), while forecasting, mechanization, and artificial intelligence are in early stages of adoption (TRL_{2-5}). Calculated average TRL for DR = $TRL_{4.82}$, highlighting the potential for agricultural innovation, however, underscoring the importance of targeted strategies to overcome barriers. Agricultural technological integration alleviates hunger and enhances food security. This encourages autarkic government policies and private sector collaboration, fostering efficient, inclusive, and environmentally sustainable agricultural practices in the Dominican Republic and across Latin American and Caribbean countries.

Keywords
Agricultural infrastructure, Productivity, Sustainability, Food security, Technology readiness level.

1. Introduction
The agricultural sector's resistance to change is a complex interplay of factors identified by Conti (2021), including embedded technologies, institutional settings, individual attitudes, political economy, infrastructural rigidities, and research priorities. Additionally, Kollmorgen (1943) and Zhang (2017) emphasize the role of culture and tradition in maintaining stability in agricultural practices. Traditional farming practices shape attitudes toward scientific progress (Jayasekara, 2021), revealing the influence of historical agricultural legacies on preferences for modern technology.

In developing countries, including the Dominican Republic in the Caribbean region, the agriculture sector's slow adoption of modern methods leads to inefficiencies and inequalities (Bualo, 2008; Vos, 2019), and faces significant challenges, creating uncertainties about its future (FAO and CDB, 2020). The Caribbean region's heavy reliance on food imports further complicates the situation (Kendall, 2009), especially in small developing economies (Bernal, 2003). These challenges are compounded by global shifts, including trade liberalization and environmental adversities (Barker, 2013). Structural hurdles and market failures exacerbate these challenges (de Janvry, 2020), with small farmers facing difficulties in adopting new technologies and enhancing productivity (Ali, 1991). Addressing these challenges requires the development of novel agricultural strategies, focusing on productivity enhancement, promoting domestic food production, and improving overall economic welfare (FAO and CDB, 2020). Government intervention is crucial, involving improvements in the business environment, removal of biased policies, and investments in rural infrastructure and agricultural research (Bualo, 2008). A comprehensive approach focusing on both the supply side (public and social interventions) and demand side (private incentives) is essential (de Janvry, 2020).

Furthermore, traditional agriculture faces notable challenges, including climate change, increased demand for goods, and crop diseases (Anderson, 2020). While traditional farming practices have been sustainable at the household level (Smil, 1994), they may fall short in addressing these challenges. However, traditional agroecological strategies, such as biodiversification, soil management, and water harvesting, can enhance resilience and productivity in the face of climate change (Altieri, 2013). The integration of new farming technologies, like vertical and organic farming, can further increase production and profitability (FAO and CDB, 2020). Therefore, a combination of traditional and modern farming practices is essential for the survival and success of the farming industry.

This research focuses on evaluating the current state of technology adoption in the agricultural sector of the Dominican Republic, aiming to understand its implications. The goal is to identify potential implementations that can bring transformative changes to how farmers operate, aligning with the broader objectives of sustainable agriculture and food security in the region. The study emphasizes key areas for improvement in agriculture, showcasing focal points and providing examples of innovative techniques and tools used globally. By addressing critical areas that require progress, the research aims to offer valuable insights and inspire solutions for driving improvement and innovation in the agricultural sector.

1.1 Agriculture in the Dominican Republic
Tourism has significantly influenced agriculture in the Dominican Republic (DR), impacting both local food production and the export portfolio. Local food production plays a crucial role in meeting the demand for fresh produce driven by the tourism industry (Meyer 2020). The country's agricultural exports have diversified, shifting from traditional items like sugar and coffee to high-value products such as cigars and cocoa beans (Meyer 2019). The potential for additional income through agro-tourism is recognized, with estimates suggesting that a well-developed industry could generate millions annually (Catalino 2004). However, the growth of tourism has also brought changes in land use and labor dynamics. Larger hotels, wielding greater buying power, have implications for local farmers and their interactions with the agricultural sector (O'Ferral 1991).

The Ministry of Economy of the Dominican Republic has reported that the country exhibits above-average levels of competitiveness in key economic sectors, including agriculture, industry, and tourism (Contreras 2023). While technology has made significant inroads in various sectors due to exponential growth and the impact of COVID-19, agriculture has been relatively slow to evolve. Numerous conventional methods continue to be widely used, perhaps because there is a perception that agricultural practices, closely connected to nature, may not seamlessly incorporate technology.

The Dominican Republic possesses a significant expanse of cultivable land, totaling 877,000 hectares. Within this, 599,200 hectares are primarily dedicated to cultivating traditional crops and cereals. Notably, there has been a substantial 69% growth in cultivation within protected environments, such as greenhouses, covering an area of 916 hectares. (Fernández 2022) (Figure 1 and 2).

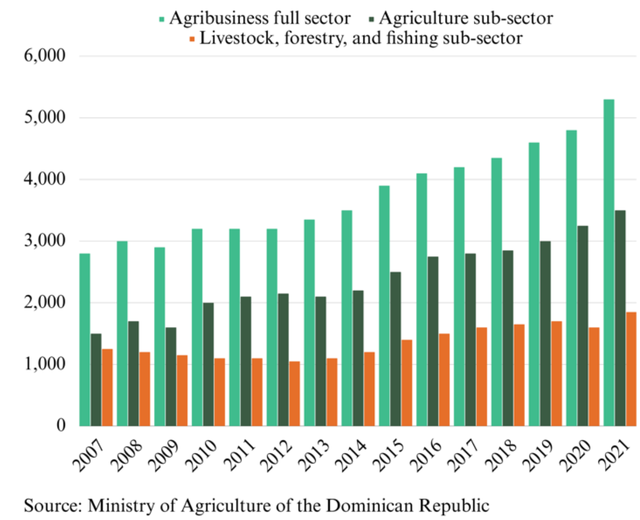

Figure 1. GDP of agricultural sector (in millions of US dollars)

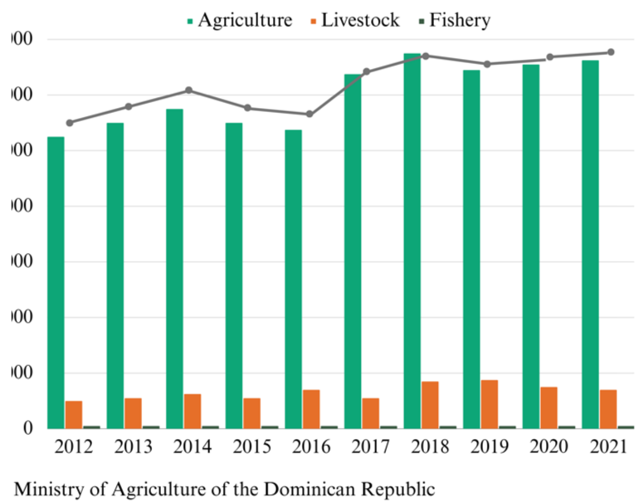

Figure 2. Evolution in agricultural production in the Dominican Republic (in tons)

The agribusiness sector significantly contributes to the Dominican Republic's GDP, constituting 5.7%, while the agriculture sub-sector accounts for 3.7% (Fernández 2022). Impressively, this sector has experienced robust growth, with its value surging from USD 1.559 billion in 2007 to USD 3.455 billion in 2021, marking a remarkable 122% increase (see Figure 1) (Fernández 2022). In the last decade, agricultural production in the Dominican Republic has demonstrated substantial progress, culminating in a total output of 13.2 million tons in 2021 (see Figure 2). This noteworthy accomplishment signifies a significant 27% increase over the span of ten years, indicating the continuous growth and development of the sector (Fernández 2022) (Table 1).

Table 1. Agricultural Land Use and Crop Distribution in the Dominican Republic

Dominican Republic	**2021**
Country's surface area	48,311 km²
Arable land area	877,000 hectares
Sown area (open field)	599,200 hectares
Traditional products (sugar cane, tobacco, coffee, cacao) (% of area planted)	37.43%
Cereals (% of area planted)	37.39%
Legumes (% of area planted)	8.24%
Roots and tubers (% of area planted)	6.07%
Musaceae (% of area planted)	4.44%
Vegetables (% of area planted)	3.26%
Fruits (% of area planted)	2.39%
Oilseeds (% of area planted)	0.79%
Surface area planted under protected environment (greenhouse)	916 hectares

In the agricultural landscape of the Dominican Republic, traditional products remain dominant, yet there is notable cultivation of fruits, bananas, and vegetables. Fruits, in particular, lead in domestic consumption, followed by cereals, bananas, vegetables, and tubers. Over the past two decades, agricultural exports have shown substantial growth, averaging an annual increase of 8%, constituting 21.6% of total exports in 2021, valued at USD 2.692 billion. Key exports include bananas, avocados, and peppers, with primary destinations being the United States, Haiti, the United Kingdom, and the Netherlands (Banco Mundial 2021).

The Dominican agricultural market is characterized by numerous small independent producers, with larger companies playing a smaller role. The government actively supports the sector through programs and financial aid, especially for small and medium-scale farmers. In terms of agricultural technology, priority sectors include machinery, irrigation systems, fertilizers, and greenhouses, with Spain being a significant supplier. The focus on fertilizers, constituting USD 35.2 million in total exports, highlights opportunities for market entry, emphasizing the importance of local partnerships due to legal safeguards for distributors.

To expand the export base and diversify production, the government emphasizes technology, training, and specialization. Opportunities identified include irrigation system expansion, fruit and vegetable classification technologies, improvements in storage and preservation, promotion of protected environment crop production, and advancements in seed production. Addressing these opportunities is crucial for successful agricultural growth in the Dominican Republic.

As the country advances its agricultural sector, challenges and opportunities align with global trends. Strides in production and export underscore the pivotal role of technology in enhancing efficiency. Prioritizing forecasting, mechanization, infrastructure development, and sustainable energy use is imperative for future food security and agricultural sustainability in the Dominican Republic.

1.2 Key areas of study

1.2.1 Forecasting

Climate change is expected to have widespread effects on food production, with increased rainfall unpredictability, more frequent droughts and floods posing challenges for crop yields, particularly in Caribbean nations. The long-term environmental repercussions, including groundwater depletion and soil degradation, will impact food and agricultural systems. Without adaptive measures, a significant worsening of food insecurity is anticipated, extending beyond supply issues to encompass food quality, accessibility, and utilization (Wyman 2018). Biotic research emphasizes genome engineering technologies for modifying biological systems, growth regulators to enhance plant resilience, and the study of plant hormones for shaping shoot and root structures (Wyman 2018). Improving forecasts through advanced models becomes crucial for enhancing agricultural productivity, sustainability, and resilience. These forecasting tools enable anticipation and adaptation to erratic rainfall patterns, guarding against adverse effects of droughts and floods, and potentially mitigating crop yield reduction, playing a pivotal role in strategically managing resources for a more resilient agricultural system.

1.2.2 Mechanization

Agricultural mechanization in Latin America signifies a vital shift from a historically labor-intensive sector to a modern and efficient model, incorporating machinery and automated processes to meet contemporary demands. Mechanization spans a range of technologies, from basic handheld tools to advanced motorized machinery. Sustainable mechanization holds the potential to reduce labor, address shortages, create jobs, enhance productivity, lower harvest costs, improve resource efficiency, and increase market accessibility (United Nations 2021). While small-scale producers face challenges in affording specialized machinery, successful investments, and digital solutions like Hello Tractor in Nigeria and TROTRO Tractor in Ghana aim to improve access to tractors, overcoming challenges of limited internet connectivity and language barriers (United Nations 2021). Mechanization also presents solutions for livestock and poultry, playing a crucial role in preventing and controlling zoonotic diseases by eliminating pathogens, blocking transmission pathways, and improving biosafety. The COVID-19 pandemic has emphasized the importance of addressing zoonotic diseases, especially in the Asia-Pacific region, where mechanization can enhance breeding efficiency and livestock product quality, leading to increased productivity through more efficient cultivation and processing methods (United Nations 2021).

1.2.3 Infrastructure
Historically, developing countries have faced significant infrastructure challenges, including inadequate water management systems, limited rural connectivity, and suboptimal post-harvest handling, all of which profoundly impact agricultural output and farmer incomes. Assessing the current state of agricultural infrastructure in these nations reveals the crucial role it plays in shaping day-to-day operations and the long-term viability of the sector. Notably, agriculture accounts for 70% of all water withdrawals, particularly affecting regions with scarce rainfall like the Middle East, North Africa, and Central Asia, where 80–90% of water withdrawals are for farming, a trend expected to persist (Raman 2017). Developing infrastructure, such as efficient irrigation systems, water storage and recovery facilities, irrigation canals, pipelines, and advanced water recycling, becomes vital in alleviating strain on natural water supplies, reducing waste, enhancing water conservation, sustaining agricultural productivity, and ensuring the long-term viability of water resources in arid and semi-arid regions.

1.2.4 Energy
The Caribbean's agricultural sector, traditionally dependent on conventional energy sources, faces the simultaneous challenges of escalating energy costs and environmental considerations. Globally, food systems currently account for 30% of accessible energy usage, contributing to about 35% of greenhouse gas emissions in food production chains, excluding those from land-use changes. A staggering one-third of produced food is wasted, leading to the loss of approximately 38% of the energy consumed in food systems. Modern food production heavily relies on fossil fuels, while around 3 billion people still rely on traditional biomass for cooking and heating, negatively impacting health, the environment, and economic growth (United Nations 2021).

2. Methodology
2.1 Technology Readiness Assessment
2.1.1 Defining Technology Readiness Levels
To effectively integrate the empirical data from site visits with technological advancements, a Technology Readiness Assessment (TRA) for the regional agricultural sector was established. This TRA utilizes a standardized framework to categorize the stages of technological development and aids in guiding investment decisions for stakeholders. By assessing Technology Readiness Levels (TRLs), it becomes possible to identify specific challenges and gaps, prioritize research, and minimize the risks associated with investing in nascent technologies. Insights from other fields' experiences with TRLs have been instrumental in aligning this approach with technological trends and regulatory considerations, ensuring the focus remains on mature, impactful agricultural solutions that can lead to significant improvements in the region's farming practices. The TRA is invaluable for identifying the most promising technologies and making strategic investments in innovations poised to positively impact the agricultural sector.

The framework consists of nine Technology Readiness Levels (TRLs), ranging from the initial phase of technology development (TRL 1) to its final stage of commercialization and widespread adoption (TRL 9). TRLs 1-3 encompass the development stages, starting with the observation and documentation of fundamental scientific principles, conceptualizing technology applications tailored for developing nations, and culminating in the creation and preliminary testing of a tangible prototype. TRLs 4-6 mark near-real operational stages, where the technology faces broader recognition yet encounters resistance, steps out of the lab for field testing in third world-like environments, and is deployed for testing in uncontrolled real-world settings of developing nations. TRLs 7-9 signify full-scale readiness, starting with pilot-scale assessments, expanding to regional and national integration, and culminating in widespread adoption and integration, demonstrating substantial improvements in local conditions (NASA 2012).

2.1.2 Calculating Technology Readiness Levels' Metrics and Risk Measures
The framework for evaluating technology maturity and readiness in the Dominican Republic's agricultural sector was developed using standardized metrics and measures from the US Department of Energy (DOE) in 2012, considering risk and uncertainty factors. The main goal is to offer a comprehensive guideline for decision-making in the development and deployment of technology. Specifically adapted to the Dominican Republic's context, the assessment focuses on determining the maturity of technologies within the country's agricultural sector.

To collect metrics for each technology, the process begins by creating a questionnaire (see table 2) with binary-choice questions (Yes/No). This questionnaire, designed for experts from various fields, aims to obtain clear and measurable responses. Focused on assessing the technology readiness level (TRL) through probability assessment (equation 1) in agricultural operations, it targets innovations and best practices in farming. The questions cover aspects like machinery usage, modern tools for farming, soil preparation, water provision systems, pest and disease protection, and record-keeping for crop yields and sales. The structured approach seeks to provide an accurate snapshot of technological adoption among local agriculturalists across different sectors. This pragmatic method ensures that data collected during on-site visits reflects the true state of technological integration in agriculture.

Equation 1.

$$P(TRL_i) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$n = (\text{total trials})$$

$$k = (\text{successful trials})$$

$$p = 0.5 \text{ (assuming it is equally likely to get a yes or no for each question)}$$

The data gathered from these questionnaire responses is analyzed to assess the readiness of the technologies. This involves counting the number of Yes/No answers for each TRL and using the probability equation based on binomial distributions $P(TRL_i)$ (see eq. 1) to build an uncertainty model (U).

The risk is assessed using cumulative probability distributions across all relevant TRLs, incorporating statistical analysis; in this case, uncertainty bounds, to estimate and visualize risks. The questionnaire and risk assessment model are iterative and undergo continuous refinement based on feedback, making the process dynamic and responsive to new insights. The probabilities are calculated using the count of Yes/No responses.

Equation 2.

$$U = \gamma_1 F(x_1) + \gamma_2 F(x_2) + \ldots + \gamma_9 F(x_9)$$

Equation 3.

$$U = (1-\alpha_4)(1-\alpha_5)F(x_3) + \alpha_4(1-\alpha_5)F(x_4) + \alpha_5 F(x_5)$$

A Cumulative Distribution Function (CDF_j) is then derived to simulate uncertainty values for each TRL. The document discusses a linear mixture problem to integrate information about partially completed TRLs, using a combination of all TRLs (see eq. 2).

Equation 4.

$$W_j = \alpha_j \prod_{i=j+1}^{9} (1-\alpha_i), \; j=1,2,\ldots,8$$
$$W_9 = \alpha_9$$

Equation 5.

$$CDF_j = \sum_{i=1}^{j} W_i$$

Finally, the simulation involves converting the calculated weights (see eq. 3) into a cumulative distribution (see eq. 4 and 5), followed by generating a random deviate (r) from a uniform distribution (0,1) and linear interpolation for each TRL realization, which fit in to provide a detailed view.

The final goal is to provide a more realistic assessment of technology readiness levels and associated risks, aiding decision-making processes for technology adoption and development.

1. Estimate uncertainty for each TRL (The uncertainty is assumed (log_{10}) normally distributed. As TRL increases, uncertainty bound decreases.)
2. Mixture problem (Probability for completing each TRL level (a_i) and uncertainty distribution for each level ($F_i(x)$) are both considered).
3. Combination of all TRLs for final uncertainty (U).
4. General mixture equation.
5. Simulating the TRL.
6. Multiple simulations.

This methodology, condensed in a step-by-step, offers a detailed and empirical evaluation of technological capabilities and potential vulnerabilities, providing critical insights for stakeholders. Such an evaluation is instrumental in guiding strategic planning and investment decisions, enabling a more calculated and efficient approach towards technology adoption and development. By understanding both the readiness and the risks, they can make more informed, effective decisions that align with the sector's needs and potential.

2.2 Integrated site evaluations

Conducting integrated site evaluations in collaboration with local agriculturists is essential for gaining a comprehensive understanding of agricultural practices. These evaluations, carried out between May and July 2023, involved visits to farms and fields of various sizes in the northern region of the Dominican Republic, known as *El Cibao* (see table 2). *El Cibao*, a crucial agricultural area, contributes significantly to the country's economy due to its fertile soil, favorable climate, and abundant water resources. The research team's direct interactions with farmers provided valuable insights into their perspectives, needs, and constraints.

El Cibao, recognized for its agricultural importance, plays a pivotal role in the nation's economy, contributing substantially to the GDP and offering ample employment opportunities. The region produces a diverse range of agricultural products (see Figure 4), including plantains, rice, and various vegetables. Plantains, in particular, stand out as leading export crops, with the Dominican Republic ranking among the global top producers. Rice serves as a staple food crop, and diverse vegetables significantly contribute to the country's agricultural sector. During the site visits, the team engaged with producers of *pitahayas* (dragon fruit), an innovative crop recently introduced to the landscape. These emerging crops diversify the agricultural sector, reducing dependence on traditional crops and opening avenues for entry into new markets, thereby expanding the country's global agricultural presence (Figure 3).

Figure 3. Site Visit Locations

Figure 4. Site Visit Products

Table 2. Site Visits Summary

Name	Location	Product	Date of Visit
1. SITE A	Navarrete, Santiago	Rice	June 13, 2023
2. SITE B	Mao, Valverde	Tomato	May 30, 2023
3. SITE C	Monte de la Jagua, Moca, Espaillat	Plantain	May 30, 2023
4. SITE D	Constanza, La Vega	Lettuce, spinach & more	July 4, 2023
5. SITE E	Constanza, La Vega	Carrot, broccoli, cauliflower & more	July 4, 2023
6. SITE F	Constanza, La Vega	Potato	July 4, 2023
7. SITE G	Villa González, Santiago	Dragonfruit	May 16, 2023

The firsthand experiences from site visits also informed the team on how to address challenges effectively and promote growth within the agricultural sector. Observing and engaging in conversations with stakeholders during these visits allowed for a meticulous approach to understanding the nuances and challenges faced in daily operations. Conversations with local stakeholders were carefully recorded and later thoroughly analyzed to extract critical context surrounding each situation. This data covered a broad spectrum of topics, such as weather conditions, crop health, pest and disease management, soil fertility, and the implementation of innovative agricultural techniques and technology. Analyzing these discussions provided a wealth of information that illuminated the specific issues and realities of the agricultural sector. In essence, site visits played a pivotal role in providing a tangible, on-ground perspective that enriched the research with practical insights and a deeper appreciation of the diverse agricultural ecosystem.

3. Results

3.1 Irrigation systems

Irrigation systems have been introduced and utilized in some third-world countries to improve water efficiency and crop yields. While the technology is not new, its adoption is still limited in certain regions due to factors such as cost, access to resources, and technical expertise. Some communities have embraced basic irrigation methods, but more advanced and efficient systems might not be widely available or affordable. Farmers that do implement irrigation systems in their fields apply it for their whole production, locating them at a level 7 according to our TRL standards. Site G is an example of a company that takes this even further by transmitting fertilizers and the exact nutrients needed for dragon fruit's optimal growth, through their fertigation system. However, Site G represents a more than average TRL because around 40% of farmers fall under the category of level 4, because they do understand the possibilities, they have with irrigation systems but prefer not to change their way of work in belief that they are profitable enough not taking into consideration how much their wastes can accumulate and mean a change in their business. Site C is in process of going through a Level 4 to Level 7 and they shared with us their reasons; they lose 20% of their production every 10 months. They are dependent from rainfall to hydrate their crops and long seasons of drought and heavy rain afterward prevents their plantains from growing as strong as needed and is one of the factors that generate these losses. They are an example of a company that has noticed that even while being profitable in agriculture, margins of wastes can be cut down.

	YES	NO
Do they have a system for providing water to their crops?	5	2

1. Initial Probability Calculation

Binomial Probability Formula

$$P(X=k)=\binom{n}{k}p^k(1-p)^{n-k}$$

where

$$n=7$$
$$k=5$$
$$p=0.5$$
$$P(X=5)=\binom{7}{5}\cdot 0.5^5\cdot(1-0.5)^{7-5}$$
$$=16.41\%$$

2. Uncertainty Estimation

Standard deviation for a binomial distribution

$$\sigma=\sqrt{n\cdot p\cdot(1-p)}$$
$$\sigma=\sqrt{7\cdot 0.5\cdot(1-0.5)}$$
$$\sigma\approx 1.323$$

3. Mixture Problem

Weighted uncertainty calculation

$$U=y_1F_1(x)+y_2F_2(x)+\ldots+y_9F_9(x)$$

$$Weights\ y_i:[7.5\%,2.5\%,2.5\%,20\%,20\%,10\%,7.5\%,20\%,10\%]\ (TRL1-9)$$
$$CDFvalues\ F_i(x):[1,1,1,0.8,0.7,0.7,0.2,0.1,0]\ (TRL1-9)$$
$$U=0.075\cdot 1+0.025\cdot 1+\ldots+0.1\cdot 0.1$$
$$U\approx 0.54 \text{ or } 54\%$$

To illustrate the process of assessing technology readiness and analyzing uncertainty, consider the step by step of the case of irrigation systems. The initial probability calculation with a value of 16.41% suggests that the chance of achieving exactly 5 successful outcomes out of 7 (with a 50% success rate for each outcome) is relatively low, indicating a moderate level of certainty in reaching this specific number of successes. The standard deviation value of 1.323 reflects the variability or dispersion of the success rates around the mean number of successful outcomes. A larger standard deviation would indicate greater variability and thus greater uncertainty. The weighted uncertainty of 54% is a composite measure that accounts for the likelihood of successful completion at various TRL levels and their associated uncertainties. A 54% uncertainty indicates that over half of the outcomes are uncertain, highlighting the need for caution in decision-making.

4. Simulation of TRL

CDF calculation:

$$F_i(i) = \sum_{j=1}^{i} W_j$$

TRL Simulation

$$TRL = \min(i) \mid CDF(i) - r > 0,\ \text{Random Deviate } (r) = 0.875$$

$$TRL\ 1-9 = [7.5\%, 10\%, 12.5\%, 32.5\%, 52.5\%, 62.5\%, 70\%, 90\%, 100\%]$$

$$TRL\ 1\ (CDF = 7.5\%) > 0.875$$

$$TRL\ 2\ (CDF = 10\%) > 0.875$$

$$TRL\ 9\ (CDF = 90\%) > 0.875\checkmark$$

Multiple Simulations

- 1000 simulations
- TRL 1-9 = [6.6%, 3.0%, 2.8%, 20.7%, 21.6%, 9.2%, 8.0%, 16.6%, 9.3%]
- TRL 1-9 = [86^{th}, 30^{th}, 28^{th}, 207^{th}, 216^{th}, 92^{th}, 80^{th}, 166^{th}, 93^{th}]
- Most frequent: TRL 4 (20.7%) + TRL 5 (21.6%)

The simulation of TRL that results in a high percentage (e.g., CDF of 90% is greater than a random deviate of 0.875) suggests a high likelihood of achieving a high level of technology readiness, indicating that the technology is mature and ready for deployment or nearing operational capability. In the multiple simulations, the most frequent TRLs give an indication of the most probable outcome based on the simulation. The most frequent TRLs represent the levels of technology readiness that are most likely to be realized given the current state of development and the uncertainties involved.

Uncertainty Application to Simulated TRL

Applied overall uncertainty (54%) to the most frequently simulated TRLs (TRL 4 and 5).

Final Analysis and Reporting

The technology is most likely at TRL 4 or 5, with a moderate level of uncertainty.

The TRA assign irrigation systems a TRL of 5, which indicate that they face resistance.

3.2 Hydroponic plantations

Agricultural infrastructure like greenhouses, hydroponic, and aquaponic systems are less common in third-world countries compared to developed nations. The adoption of these structures is often hindered by the initial investment cost, maintenance requirements, and the need for specialized knowledge. While they hold promise for improving crop production and resource efficiency, they are still at a relatively early stage of adoption in many regions. Constanza is a town that is primarily based on agriculture. During the visit, the team observed an impressive hydroponic plantation, showcasing the immense potential that technology holds for agriculture. This innovative system allows crops to grow without soil contact, leading to cleaner and more efficient growth. It also significantly reduces the time it takes for crops to reach maturity, sometimes up to 50%, making it a highly promising solution for the future of farming.

One of the most exciting aspects of hydroponic plantations is their environmental impact. Operating with minimal waste, they contribute positively to sustainability efforts. Additionally, the vertical growth approach maximizes workspace efficiency by enabling farmers to grow crops upward, rather than relying solely on horizontal land usage. As fertile land becomes scarcer, hydroponic plantations hold the potential to revolutionize agriculture by facilitating the construction of agricultural skyscrapers.

Currently, hydroponic plantations are produced and sold on a relatively small scale, placing them at level 6 in terms of technological readiness. Moreover, their significance in the realm of agricultural infrastructure adds further value to their readiness level, making them a promising investment for the future of sustainable farming.

	YES	NO
Do they employ hydroponic systems?	3	4

Initial Probability Calculation

Binomial Probability Formula

$$P(X = k) = 27.34\%$$

Uncertainty Estimation

Standard deviation for a binomial distribution

$$\sigma \approx 1.323$$

Mixture Problem

Weighted uncertainty calculation

$$U \approx 0.588 \text{ or } 59\%$$

Simulation of TRL

$$\text{Random Deviate } (r) = 0.725$$

$$TRL\ 8\ (CDF = 90\%) > 0.725 \checkmark$$

Multiple Simulations

Most frequent: TRL 5 (23.7%) + TRL 6 (24.8%)

Uncertainty Application to Simulated TRL

Applied overall uncertainty (59%) to the most frequently simulated TRLs (TRL 5 and 6).

Final Analysis and Reporting

The technology is most likely at TRL 5 or 6, with a moderate level of uncertainty.

The TRA assigns hydroponic plantations a TRL of 6, which indicate that they show promise but lack cost efficiency.

3.3 Genetically modified crops

Genetically modified crops represent the longest-standing technological area in agriculture. Consequently, it is common to find such crops in even third-world countries. Whether an independent farmer or a farmer with minimal modernization, they all have the option to choose genetically modified seeds for their plantations. For instance, Site B utilizes genetically modified tomato seeds that offer increased disease resistance and can regrow up to five times before replanting is needed. Similarly, Site C plants genetically modified plantains, which result in higher production and larger products per season. This long-standing practice demonstrates a TRL of 9, as it has been implemented in the country for many years and the population has witnessed its positive impact, such as year-round availability of crops and larger food products.

	YES	NO
Do they use any technology to protect their crops from pests or diseases?	7	0

Initial Probability Calculation

Binomial Probability Formula

$$P(X = k) = 0.78\%$$

Uncertainty Estimation

Standard deviation for a binomial distribution

$$\sigma \approx 1.323$$

Mixture Problem

Weighted uncertainty calculation

$$U \approx 0.836 \text{ or } 84\%$$

Simulation of TRL

$$\text{Random Deviate } (r) = 0.64$$

$$TRL\ 6\ (CDF = 62.5\%) > 0.64\checkmark$$

Multiple Simulations

Most frequent: TRL 8 (21.8%) + TRL 9 (28.8%)

Uncertainty Application to Simulated TRL

Applied overall uncertainty (87%) to the most frequently simulated TRLs (TRL 8 and 9).

Final Analysis and Reporting

The technology is most likely at TRL 8 or 9, with a high level of uncertainty.

The TRA assign genetically modified crops a TRL of 9, which indicate that they demonstrate long-standing acceptance.

3.4 Forecasting (weather, pests, diseases)

Forecasting technologies in agriculture, such as weather forecasting and pest/disease prediction, are gradually becoming more accessible in most developing countries through mobile apps and online services. However, their accuracy and coverage can vary, and challenges such as limited internet connectivity and technological infrastructure in rural areas may hinder their implementation.

During the site visits, it was observed that advanced technologies like smart mechanization and artificial intelligence were not widely present in the agricultural practices of the Dominican Republic. These technologies, well-established in developed nations, are still in early stages of adoption in many developing countries due to challenges like initial investment costs, technical expertise, and limited access to resources, which impede their widespread implementation. A common issue noticed during the visits was the lack of prediction or accountability for wastes. Many farms assume a certain percentage of waste and work to reduce it without a specific strategy. Site F is an example, having a continuous flow of unaccounted waste. Similarly, there is imprecision in production counting. Site C estimates the amount of product in each plantain bunch, leading to discrepancies between client orders and actual quantity received, resulting in additional costs for deliveries or returns. Site B also requires a better forecasting system for counting, as they pay workers based on the amount of product collected. Improved predictions would allow them to track daily collection targets more effectively.

	YES	NO
Do they keep any basic records of their crop yields and activities?	3	4
Is there any basic use of weather forecasts or monitoring of climate conditions for farming decisions?	3	4

Initial Probability Calculation

Binomial Probability Formula

$$P(X = k) = 20.33\%$$

Uncertainty Estimation

Standard deviation for a binomial distribution

$$\sigma \approx 1.871$$

Mixture Problem

Weighted uncertainty calculation

$$U \approx 0.27 \text{ or } 27\%$$

Simulation of TRL

$$\text{Random Deviate } (r) = 0.168$$

$$TRL\ 2\ (CDF = 20\%) > 0.168 \checkmark$$

Multiple Simulations

Most frequent: TRL 1 (13%) + TRL 2 (40%)

Uncertainty Application to Simulated TRL

Applied overall uncertainty (27%) to the most frequently simulated TRLs (TRL 1 and 2).

Final Analysis and Reporting

The TRA assigns forecasting a TRL of 2 which indicate that it's in its early stages of adoption.

The technology is most likely at TRL 1 or 2, with a low level of uncertainty.

3.5 Mechanization (tractors, harvesters, drones):

Mechanization in agriculture, such as the use of tractors and basic machinery, is found in varying degrees in some developing countries. However, its implementation may be limited to larger-scale commercial farms, and smallholder farmers could face challenges in accessing such equipment due to cost and availability.

In certain developing countries, drones are sparingly being used for monitoring and data collection purposes. However, their adoption is generally limited to specific applications like crop monitoring or surveying due to various challenges related to regulations, affordability, and training. While the potential benefits of drones are recognized, the technology is still relatively new and not yet widely deployed in the agricultural sector. Site G's limited use of drones for land surveying and altitude recording exemplifies this, representing a TRL 5, as it has been utilized on a small scale primarily for testing purposes rather than for practical improvements in farming practices.

As for advanced smart tractors and harvesters, their availability and accessibility are limited in most developing countries. While some prototypes and pilot projects exist, broader implementation faces obstacles, including affordability, technical knowledge, and support infrastructure.

During the visits to Site A, Site B, and Site C, it was observed that laborers tend to prefer traditional harvesting knives over newer implementations, despite the potential benefits of improved efficiency and reduced physical strain. This represents a TRL 4, indicating a level where certain advancements have been tested and introduced but have not yet achieved widespread adoption due to factors like user familiarity and comfort with traditional practices.

	YES	NO
Do they use machines for planting and harvesting crops?	2	5
Do they use modern equipment for plowing and soil preparation?	7	0
Is there any evidence of basic automation in the handling or processing of crops?	3	4

Initial Probability Calculation

Binomial Probability Formula

$$P(X = k) = 14.02\%$$

Uncertainty Estimation

Standard deviation for a binomial distribution

$$\sigma \approx 2.29$$

Mixture Problem

Weighted uncertainty calculation

$$U \approx 0.27 \text{ or } 27\%$$

Simulation of TRL

$$\text{Random Deviate } (r) = 0.21$$

$$TRL\ 7\ (CDF = 82.5\%) > 0.21 \checkmark$$

Multiple Simulations

Uncertainty Application to Simulated TRL

Applied overall uncertainty (49%) to the most frequently simulated TRLs (TRL 4 and 5).

Final Analysis and Reporting

The technology is most likely at TRL 4 or 5, with a moderate level of uncertainty.

The TRA assigns mechanization a TRL of 5 which indicate that it's in its early stages of adoption.

3.6 Artificial Intelligence (AI) in agriculture

Applications of AI in agriculture are currently in their early stages of development across most third-world countries. While there are ongoing research initiatives and pilot projects, the widespread implementation of AI technologies in farming practices remains limited. Challenges such as data availability, technical expertise, and infrastructure constraints present obstacles to the broader adoption of AI-based solutions.

One of the primary reasons why AI applications in agriculture are still at an early stage is that many other foundational technologies need to be established first. For example, AI can be integrated into irrigation systems, drones, and tractors, but significant progress needs to be made in each of these areas before effectively incorporating AI. As a result, the evolution of AI in agriculture relies on the successful integration of other technologies and practices to create a solid foundation for its implementation.

	YES	NO
Is there any evidence of basic artificial intelligence in the farm?	1	6

Initial Probability Calculation

Binomial Probability Formula

$$P(X = k) = 0.78\%$$

Uncertainty Estimation

Standard deviation for a binomial distribution

$$\sigma \approx 1.323$$

Mixture Problem

Weighted uncertainty calculation

$$U \approx 0.24 \text{ or } 24\%$$

Simulation of TRL

$$\text{Random Deviate } (r) = 0.499$$

$$TRL\ 5\ (CDF = 62.5\%) > 0.499 \checkmark$$

Multiple Simulations

Most frequent: TRL 1 (25%) + TRL 2 (43%)

Uncertainty Application to Simulated TRL

Applied overall uncertainty (24%) to the most frequently simulated TRLs (TRL 1 and 2).

Final Analysis and Reporting

The technology is most likely at TRL 1 or 2, with a low level of uncertainty.

The TRA assigns artificial intelligence a TRL of 2 which indicate that it's in its early stages of adoption.

3.7 Analysis

Technologies assessed and their respective readiness levels:

- Irrigation system = TRL 5
- Hydroponic system = TRL
- GMO Crops = TRL 9
- Forecasting = TRL 2
- Mechanization = TRL 5
- Artificial Technology = TRL 2
- Overall (calculated average for the country) = TRL 4.83

This assessment provides individual Technology Readiness Levels for different aspects of agricultural technology, indicating the maturity and integration level of each. The overall average TRL of 4.83 is a composite score that gives a general sense of the current state of technology readiness in agriculture, suggesting that there is a moderate level of technological development in this sector, which highlights the potential for agricultural innovation, however, underscores the importance of targeted strategies to overcome barriers.

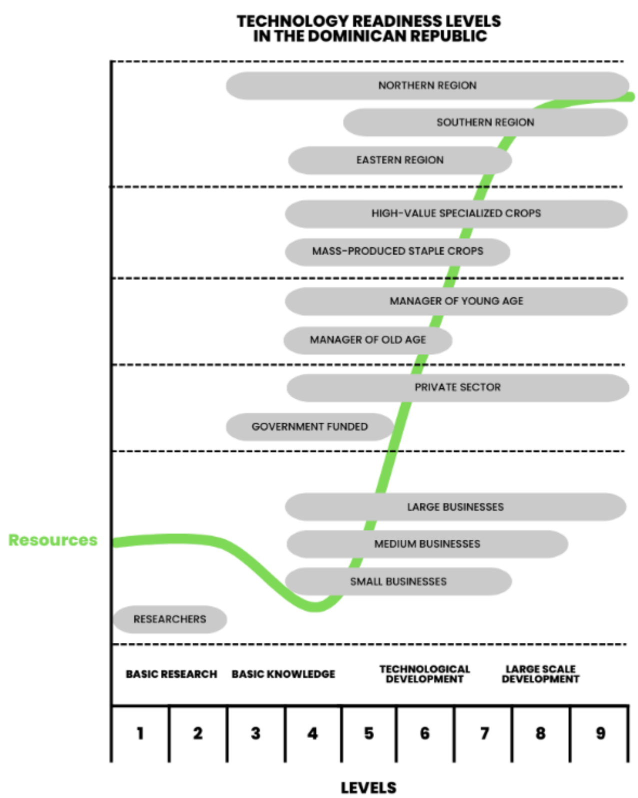

Figure 5. Graphical Overview of TRL Metrics and Tendencies in the DR

After performing TRAs on different agricultural sectors, TRLs can be represented visually (see figure 5) to show how factors such as geographic regions, types of crops, age of management, funding sources, and business size correlate with different stages of technological development. The gradations along the TRL spectrum indicate that high-value specialized crops, the private sector, and large businesses are further along in adopting advanced technologies, while other areas like mass-produced staple crops and smaller businesses are at earlier stages of technological integration. The green lines connecting to the 'Resources' axis suggest the influence of investment and research on technology adoption, highlighting the disparities and potential areas for targeted growth in the sector.

4. Conclusion

The study presented a comprehensive overview of the current state of agricultural technology in the Dominican Republic and Latin America. It emphasized the potential that innovative solutions have, to enhance agricultural productivity and resilience. An analysis of the Technology Readiness Levels (TRLs) revealed numerous opportunities and challenges, with the Dominican Republic displaying an average TRL of 4.83.

Findings suggest a considerable interest in agricultural technology among farmers, though actual adoption rates differ markedly among technologies. Barriers such as high initial costs, the need for specialized knowledge, and the inclination towards established farming techniques are predominant. Nonetheless, the gradual implementation of technologies, including efficient irrigation systems and advanced agricultural infrastructure, could greatly enhance agricultural output.

The importance of technology in propelling the agricultural sector forward in both Latin America and the Dominican Republic was a key point of the study. Technological advances can help tackle significant challenges like variable weather patterns, pest control, and the efficient use of resources. They also offer a means for Latin American nations to enhance their competitiveness on a global scale.

The benefits of adopting new agricultural technologies include improved water management through advanced irrigation systems, which can decrease waste and bolster crop vitality. Additionally, mechanization and artificial intelligence could improve crop management, cut labor costs, and bolster productivity. The adoption of biotechnologies can lead to crops with greater disease resistance, thereby enhancing yields.

The study advocates for more research aimed at overcoming the hurdles to technology adoption within the agricultural sector. It calls for investigations into affordable, user-friendly technologies suited to local needs, as well as studies to understand farmer attitudes toward new technologies and how to foster their adoption. Furthermore, educational initiatives to increase farmer expertise in emerging technologies are seen as crucial for future progress.

In conclusion, technology and innovation are essential to revolutionizing agriculture in Latin America and the Dominican Republic. Despite existing challenges, strategic investment, education, and governmental support can lead to the widespread implementation of advanced agricultural technologies, marking a new era of robust and efficient farming in the region.

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Acknowledgements

We acknowledge Richard Olawoyin's leadership and mentorship, pushing us beyond boundaries. Wendy Jacobo, Levis Cabrera, and Pontificia Universidad Católica Madre y Maestra provided critical expertise and unwavering support. Collaborations with Tropihaya, Micardi, Tocantins Trading, Arroz Bisonó, Espalsa, Granja Gian José, and

Agroprecisión Dominicana, as well as with, Silvio Carrasco, Fernando Díaz, and Jahn Fabián enhanced our research, advancing agricultural technology readiness. Gratitude to all for their crucial contributions.

Biographies

Andy R. Tineo is a graduate in Industrial and Systems Engineering from Pontificia Universidad Católica Madre y Maestra (PUCMM). His academic pursuits are complemented by certifications in Logistics and SCM within ISE at PUCMM, Money Laundering Prevention, and Risk Management. His thesis project, advised by Richard Olawoyin, Ph.D., P.E., received great acclaim. Tineo's entrepreneurial spirit was ignited at a young age, launching his first business, Cibao Auto Parts, at 16, specializing in automotive part import and export. His professional journey includes significant contributions to Constructora Realty, a leading construction and real estate company. Presently, Andy is deeply engaged in the U.S. stock market, showcasing his adaptability and acumen in the financial domain. As president of COOPREALTY, he oversees significant financial assets, managing over 500 million pesos. His career, spanning construction, real estate, and finance, reflects a dynamic and versatile professional ethos.

Almanzor E. Vila is an honors graduate in Industrial and Systems Engineering from Pontificia Universidad Católica Madre y Maestra (PUCMM). He was also Salutatorian at Santiago Christian School (SCS). He served as the internal relations officer, led the advertising and graphic design department and delivery of the twenty-eighth Seminar "INSIGHT: Un vistazo hacia la industria dominicana" of the ISE Student Committee. He completed a certification in Logistics and SCM within ISE at PUCMM. His thesis project, advised by Richard Olawoyin, Ph.D., P.E., received great acclaim. Almanzor earned the title of Best Young Banker during his internship in the corporate services department at Banco Popular, the largest private bank in the country. He also completed a successful organizational restructuring during his internship in the maintenance department at La Fabril, a leading food processing industry, where he currently is the Improvement Engineer. Additionally, he manages several vacation properties across the country.

Richard Olawoyin, associate professor of Industrial and Systems Engineering at Oakland University (OU) and U.S. Fulbright Scholar. He is professional engineer (P.E.) with multidisciplinary research interests in stochastic system optimization and functional system safety analysis. He received his PhD in Energy Engineering from Penn. State University. He serves as the faculty adviser for NSBE at OU since 2014. He is the Chair of the ABET Inclusion Diversity and Equity Advisory (IDEA) Council. He has received multiple awards including the ASSP Charles V. Culbertson Outstanding Award in 2019 and 2022, and the 2023 Fulbright Scholarship for teaching and research.