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# Social technologies for inclusive development: multilevel policy and practices

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# Social technologies for inclusive development: multilevel policy and practices

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# Editorial: Social technologies for inclusive development: multilevel policy and practices

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Editorial on the Research Topic
Social technologies for inclusive development: multilevel policy and practices

This Research Topic presents a wide range of articles that position *social technology* as a key enabler of inclusive development across Latin America. By understanding social technology as situated knowledge and practice—rooted in local needs and shaped by social, cultural, and institutional contexts—this collection challenges traditional paradigms that treat technology as neutral, apolitical, or universally applicable. Instead, it embraces a Latin American perspective that highlights social technologies as tools for empowerment, cultural survival, and equity.

From case studies to policy analyses, the eight contributions gathered here reflect a transdisciplinary and practice-based approach. They explore how social technologies are used to address migration, food sovereignty, educational access, gender equity, and digital inclusion—often in regions with limited infrastructure and historical exclusion. These texts collectively illustrate how the design, implementation, and appropriation of technology can reflect or resist dominant power structures, and why inclusive development requires both digital innovation and social imagination.

Cabrera-Medina et al. analyze how digital technologies are deployed to manage migration across the United States, Mexico, Honduras, and Chile. While countries like the U.S. focus on biometric control systems, others such as Chile have adopted platforms like *Migrapp* to support migrant integration. The authors highlight the uneven landscape of migration technology and argue for a rights-based, people-centered approach—what they call "responsible design"—to ensure digital tools bridge gaps rather than reinforce exclusion.

In the agricultural domain, Apablaza critically examines how Industry 4.0 technologies, such as automation and artificial intelligence, are transforming Brazil's small-scale family farming. The analysis reveals that without public support, training, and inclusive governance, these tools risk exacerbating rural inequalities. Likewise, 10.3389/fcomm.2024.1505445 Lucki documents how limited infrastructure, cultural disconnection, and institutional fragility in Guatemala's western highlands undermine the potential of agricultural digitalization. Both contributions call for community-driven, context-sensitive strategies to avoid deepening the digital divide.

Grounded in food sovereignty and ancestral knowledge, Lugo Montilla and Águas present a compelling case from the Venezuelan Andes, where smallholder farmers use both traditional and modern techniques to rescue native potato seeds. The use of *tinopós* (underground storage spaces) and community breeding methods demonstrates how grassroots innovation can preserve agrobiodiversity, strengthen local economies, and challenge the technocentric logic of industrial agriculture.

Related to education, Bonilla et al. present INDESGUA as a successful community case of knowledge management as social technology. The non-profit connects rural youth and Indigenous communities in Guatemala with international scholarship opportunities, mediating between global funding organizations and local students. Through curated information, mentorship, and contextual guidance, INDESGUA overcomes structural barriers to higher education and fosters human capital development.

The use of digital tools for women's empowerment appears strongly in two articles. Figueroa and Alvarez Lemus evaluate a mentoring program for women in STEM in Mexico. The initiative combined online platforms, messaging groups, and virtual training, leading to measurable improvements in leadership, self-confidence, and professional development among participants. In parallel, Ortiz Osejo et al. present a mixed-methods study on Digital Community Centers (DCCs) in rural northern Guatemala. The study documents how internet access, digital skills training, and workshops on positive masculinities helped empower Indigenous Mayan women, expand their economic activities, and shift gender norms within the community. Despite persistent challenges like budget constraints and weak infrastructure, the DCCs illustrate the transformative potential of inclusive, community-led digital spaces.

The final contribution, Huete-Pérez et al., reflects on regional science, technology, and innovation (STI) policies in Nicaragua, Honduras, Guatemala, and El Salvador. The authors emphasize the chronic underinvestment in R&D and institutional weaknesses that hinder inclusive innovation. They call for systemic reforms, cross-sector collaboration, and the promotion of science diplomacy to build resilient innovation ecosystems that serve the region's development goals.

Taken together, these eight articles demonstrate that social technologies are not simply tools—they are processes shaped by values, power, and participation. Whether preserving native seeds, navigating migration, or mentoring young scientists, each contribution points to the importance of locally grounded, culturally relevant, and socially just approaches to technology adoption.

Across the board, several key themes emerge. First, many of these initiatives are driven by intermediary actors—platforms, organizations, or local networks—that translate between global resources and local needs. Second, capacity-building is central: communities must be empowered not just to access technology, but to adapt it, question it, and lead its use. Third, public institutions and policy frameworks matter. Without consistent investment, inclusive governance, and attention to equity, even the most promising technologies will fall short of their transformative potential.

This Research Topic reaffirms that inclusive development is not a byproduct of innovation—it must be a deliberate objective. Social technologies, when rooted in participation, culture, and context, offer powerful pathways to transform Latin America's most pressing challenges into opportunities for collective advancement.

We thank the authors, reviewers, and communities whose work enriches this collection. Their contributions not only inform academic discourse but inspire action among policymakers, practitioners, and local leaders seeking to co-create equitable, resilient, and digitally inclusive futures.

## Author contributions

KB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. EB-L: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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# Industry 4.0: a critical reflection on its impacts on family farming

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This paper identifies groups of disruptive technologies within the framework of Industry 4.0 that can advance and integrate sustainable rural development processes. Technological advances are described and an analysis is made of the possible positive and negative effects of their implementation in family and sustainable agriculture in Brazil. To support family farming's innovative potential here, the restructuring of existing power relations and higher levels of participation, training, and education are required.

KEYWORDS

**Industry 4.0, sustainable rural development, family farming, innovation strategies, disruptive technologies**

## 1 Introduction

In contemporary society, technology has become an indispensable component of daily life, seamlessly integrated into a wide range of activities. From ordering food and watching movies to communicating with friends and navigating transportation, technological devices have become ubiquitous. This pervasive presence of technology underscores its profound influence on modern lifestyles and interactions.

Technological advancements have significantly impacted the means of production, revolutionizing both industrial and agricultural sectors. Consequently, these developments have fundamentally altered the nature of work itself. Schwab (2016, p. 18) highlights pivotal moments of "revolution" in our social and economic structures, often driven by technological innovations and shifts in societal perspectives.

The author posits that one of the earliest major transformations in human lifestyles occurred with the transition from hunter-gatherer societies to agricultural ones. This shift necessitated new approaches to work, combining human and animal labor to optimize food production.

Following the shifts in food production, the world experienced a series of profound transformations. Urban centers began to emerge, and mechanical power gradually supplanted muscle power, a defining characteristic of the industrial revolutions (Schwab, 2016, p. 18).

The first industrial revolution (1784) was primarily characterized by the mechanization of various activities, with steam engines and railroads playing pivotal roles. The second industrial revolution (1870) was marked by the adoption of electricity and the implementation of mass production techniques in industries. The third industrial revolution (1969) witnessed significant advancements in science, digital technologies, computers, telecommunications, and many of the technologies that continue to shape our lives today (Kagermann et al., 2013, p. 13).

The ongoing fourth industrial revolution is characterized by a wide range of technological possibilities across the industrial, service, and agricultural sectors. Unlike its predecessor, which primarily focused on industrial applications, the fourth industrial revolution offers a broader spectrum of technological advancements.

While some countries have already begun to integrate fourth industrial revolution technologies into their agricultural sectors, the adoption of these technologies is uneven, often limited to well-resourced farmers. Given this disparity, it is crucial to consider how these technologies can be effectively integrated into agricultural practices that may not have a high level of capitalization.

In pursuit of its "17 Sustainable Development Goals" outlined in the 2030 Agenda[1], the United Nations has established Goal 2 with the aim of eradicating all forms of hunger and malnutrition by 2030. To achieve this ambitious target, the agenda prioritizes several key objectives.

Among these objectives, Goal 2.a emphasizes the importance of increasing investments in rural infrastructure development. By enhancing infrastructure, the agenda seeks to support sustainable agricultural practices and improve access to markets for rural communities. Additionally, Goal 2.4 focuses on promoting technological advancements through research and extension services. The goal is to foster the development of sustainable food production systems and implement robust agricultural practices that can contribute to global food security.

The confluence of the fourth industrial revolution's technological advancements and the imperative to strengthen sustainable family farming in developing countries presents a promising avenue for innovation. By integrating technological solutions into family farming practices, it is possible to positively impact various segments of the agricultural value chain.

A Critical question that arises in this context is: What specific technological and disruptive innovations can contribute to sustainable development in family farming? This exploration aims to identify potential solutions that can enhance the productivity, resilience, and sustainability of small-scale agricultural enterprises.

To address the question of how disruptive technologies of Industry 4.0 can be adapted by family farming, this research aims to critically analyze these technologies and their potential applications in the context of small-scale agriculture.

The research will involve a comprehensive review of existing literature on Industry 4.0 and family farming. This review will encompass global and Brazilian perspectives on Industry 4.0, as well as an examination of specific disruptive technologies identified by Schwab (2016). The analysis will consider both the potential benefits and challenges that these technologies may pose for family farming.

Furthermore, the research will delve into the current capabilities and limitations of family farming in generating innovative and sustainable rural development processes. By exploring these factors, the study will contribute to a deeper understanding of the potential synergies and challenges associated with integrating Industry 4.0 technologies into family farming practices.

## 2 Transition to big industry and the formation of the Modern Industrial Corporation

The transition from manufacturing to big industry was characterized by a significant disruption in the traditional work processes. This disruption was primarily driven by the escalating productivity of labor, which accelerated production speed and fostered automation. Underlying this transformation was a shift in the composition of capital, a process that Marx (1867) described as a gradual evolution from a statist society to the Industrial Revolution. This evolution coincided with a relative decline in variable capital and a corresponding increase in constant capital, reflecting the progressive accumulation and concentration of wealth (Hobsbawm, 1962; Harvey, 2001, 1982).

The pivotal factor in the rupture caused by rising labor productivity during the transition to big industry lies in the relationship between the technical and organic components of capital. The technical component, responsible for augmenting the mass of the means of production, operates in contrast to the organic component, which represents the mass of labor power that sets these means in motion (Marx, 1867; Foster, 2014; Mokyr, 2002).

As the means of production expanded exponentially, the demand for labor experienced a disproportionate shift. The organic component, reflecting the value composition of capital, demonstrated a growth in constant capital relative to variable capital (Marx, 1867). This divergence meant that the demand for labor could increase or decrease independently of the proportional growth in the mass of the means of production.

Marx's law of the falling rate of profit, as articulated in his analysis of capital accumulation (2013), posits that constant capital tends to increase relative to variable capital over time. This trend, driven by the transformation of the composition of capital, significantly influenced the dynamics of big industry compared to its manufacturing predecessor.

The increasing dominance of constant capital in the production process facilitated the progressive displacement of the workforce through technological advancements and the reorganization of work. This shift toward technification and mass production was a key strategy for accumulating capital. As the organic composition of capital grew with accumulation, there was a concomitant tendency toward the concentration and centralization of capital. This concentration was fueled by competition and credit, which enabled businesses to invest frequently in technological progress and the development of new technical compositions.

In the context of expanded reproduction, where a portion of newly created value is allocated to increasing the scale of accumulation, the goal is to reduce costs through mass production and lower commodity prices. This strategy aligns with the trend toward a higher organic composition of capital, as it necessitates greater investment in machinery and technology while potentially reducing the demand for labor.

1 Agenda 2030: The 17 Sustainable Development Goals. Available at: http://www.agenda2030.org.br/ods/17/ (accessed March 12, 2021).

The consequences of these transformations, stemming from the expansion of production scales, the accelerated generation of surplus value, and the cyclical reinvestment of surplus value into capital, had profound implications for the dynamics of the capitalist system, as well as for the nature and application of productive labor. The result was the relentless growth of constant capital at the expense of variable capital, coupled with a regulated control over wages. This structural shift entailed a more rapid expansion of the sector producing means of production compared to the sector dedicated to consumer goods. This disproportionate growth forms a central aspect of the cyclical behavior inherent to the capitalist mode of production, as it both arises from and further propels the accumulation of capital. The system's logic is not primarily oriented toward the production of consumer goods, but rather toward the continual production of means of production. Consequently, this sector's development is notably accelerated due to the concurrent expansion and centralization of total capital, alongside the modernization of existing capital through technological advancements. These processes underscore the system's inherent drive toward capital accumulation rather than the direct satisfaction of consumer needs, thus reinforcing its cyclical and self-sustaining nature (Marx, 1867; Hobsbawm, 1999; Foster, 2014; Harvey, 1982).

The transformations in the productive forces of labor, driven by technological advancements and the accumulation of capital, have inadvertently eroded the foundation upon which the capitalist system rests. By reducing the number of workers engaged in value-creating activities, these changes diminish the pool of labor from which surplus value can be extracted.

This inherent contradiction within the capitalist system has significantly modified the organic composition of capital, leading to repercussions for wage regulation. One such consequence is the generation of an "industrial reserve army," a concept introduced by Marx. This surplus labor pool exerts downward pressure on wages, as workers compete for limited employment opportunities. Additionally, increased productivity can lead to a reduction in the value of labor power, as the time required to produce a unit of value decreases.

The displacement of workers due to technological advancements, a hallmark of the transition to big industry, created a pool of unemployed individuals at the disposal of capital during periods of expansion. This phenomenon served as a mechanism for maintaining wages at subsistence levels within the capitalist system.

Moreover, the growth in productivity itself tended to exert downward pressure on wages. The logic of accumulation, coupled with the creation of an industrial reserve army, disciplined the workforce. This reserve not only enabled capitalists to extract a greater amount of labor from a smaller number of workers but also facilitated the replacement of skilled workers with less skilled ones. The resulting overwork of these less skilled workers became a source of wealth for individual capitalists (Marx, 1867; Harvey, 2001, 1982).

In summary, the transition to big industry fundamentally altered the relationship between productive labor, constant capital, and wages. Productive work became increasingly conditioned by the dynamics of constant capital accumulation, while wages were subject to fluctuations influenced by the industrial cycle and the availability of labor.

Classical administration and scientific management as new ways of organizing companies and work provided planning and management of individualized positions to try to solve problems of coordinating complex functions and subordination of work. Both became, based on the structural changes that oligopolistic capitalism was developing in the context of the Second Industrial Revolution, two critical challenges that needed to be overcome in order to guarantee the acceleration of productivity growth and the potentialization of capital accumulation in accordance with an increasingly mechanized, bureaucratized and routine way of life.

The first significant transformation stemmed from the emergence of a new competitive paradigm centered on innovation, aimed at differentiating and diversifying both production processes and industries. This shift was driven by the improvement or creation of new products, the establishment of higher barriers to market entry through substantial investments in research and development (R&D), and the implementation of strategic market planning. The second transformation arose from the increasing integration of science into the innovation process. This development facilitated the rise of new industrial sectors and marked a substantial transition from labor-intensive production to mechanization. Moreover, the innovation process—whether inventive or incremental—became internalized within firms, evolving from an external phenomenon into an institutionalized function through the creation of dedicated R&D departments. Lastly, the third transformation was characterized by an unprecedented concentration of capital, which promoted the formation of corporations. This shift gradually led to the decline of individual capitalists, as shareholders emerged as collective actors, consolidating and centralizing capital through the development of competitive markets and the incorporation of technology into the production process (Quadros Carvalho, 2021).

The Modern Industrial Corporation (MIC) emerged as both a coordination and subordination mechanism, designed to address the two key challenges mentioned previously: first, the need for speed, safety, and efficiency in production processes, and second, the necessity of controlling both the timing and content of workers' labor. Classical management theory, whose foundational ideas can be traced back to Charles Babbage, developed a coordination and macro-organizational framework that combined military and engineering principles. The primary objective of this framework was to establish a systematic process of "planning, organizing, directing, coordinating, and controlling." This approach was operationalized through methodologies such as "management by objectives (MBO)," the systems of budget planning and programming, and other techniques that emphasized comprehensive national planning and control (Morgan, 2006).

The organic growth of the Modern Industrial Corporation (MIC) also shaped the organizational culture of companies from a more rational managerial perspective. The most successful firms were those that effectively rationalized their production units, as their organizational structures adapted to market dominance achieved through acquisition and merger processes, resulting in increased centralization. As noted by Quadros Carvalho (2021), during this organizational phase, centralization primarily targeted

decision-making processes, while integration encompassed the incorporation of new activities such as marketing, which played a key role in the development of new products driven by both R&D outcomes and market demand. Furthermore, segmentation involved the creation of new business areas with incremental costs managed in line with the economic cycle, and departmentalization fostered the specialization of functions within the firm, promoting efficiency and further enhancing organizational control.

In the macro-organization phase, as emphasized by Quadros Carvalho (2021), a pivotal idea emerged: the company must exercise complete control over its processes, allowing it to plan meticulously, regulate all variables, and anticipate potential problems. This approach underscored the importance of comprehensive oversight in modern industrial management. Engineers, in this context, became the driving force behind the social relations of modern capitalism, taking on both technical and managerial roles. Their influence extended to the creation of an intelligence center within the corporation, comprising key departments such as marketing, R&D, engineering, and finance.

Departmentalization during this phase advanced toward an increasingly rigorous specialization, dividing work technically according to the specific nature of tasks and strategic organizational functions. Furthermore, a strategic monitoring structure was established to oversee the creation of semi-independent business units, enhancing flexibility within the organization while maintaining centralized oversight. This entire system was built upon a vertical organizational structure, where communication flowed hierarchically, and the chain of command took precedence over technical authority, reinforcing the centralized control of decision-making and operations within the corporation.

> "The changes in organizational structure thus produced were aimed at operating as precisely as possible within frameworks of authority, for example, in terms of job responsibilities and the right to give orders and demand obedience. Patterns of authority serve as points of resistance and coordinate activities, restricting them in certain directions and encouraging them in others" (Morgan, 2006).

Technical management, as pioneered by Frederick Taylor, introduced a systematic mechanism for subordinating labor with the explicit objective of controlling both the time and content of workers' tasks. This approach, as described by Morgan (2006), "called for detailed observation and measurement of even the most routine work to discover the best way of doing things." To achieve this, the strategic planning of technical personnel required a comprehensive consideration of the entire production process, aimed at identifying the most efficient methods. Workers were then assigned specialized tasks, for which they were trained to execute with precision.

This process fostered a work environment heavily oriented toward productivity, where machines, technology, and the pace of work took precedence over the workers themselves. Under this model, laborers became subordinated to the technological systems in place, with their roles reduced to serving the demands of the production process. As Morgan (2006) notes, workers were ultimately transformed into "servants or accessories," subordinated to the technical and mechanical imperatives of the industrial system, highlighting the dehumanizing aspects of Taylorism within the capitalist production model.

The basic principles of scientific management can be summarized as follows: the control and discipline of workers' knowledge under management authority, the selection and training of workers, and the detailed planning and control of work processes. The first principle involves a systematic study of workers' elementary movements, with the goal of distinguishing between useful and inefficient actions. This analysis aims to increase the intensity of labor by optimizing the time required to complete specific tasks, using the ideal pace of work as a benchmark for evaluation. Through this process, management gains greater control over the labor process, ensuring that workers' knowledge and actions align with the company's efficiency objectives, ultimately subordinating worker autonomy to the imperatives of productivity.

The second principle of scientific management is closely linked to the first, as the detailed analysis of tasks enables management to more effectively select the right worker for each specific role, irrespective of the individual's prior skills or knowledge related to the task. This principle emphasizes the alignment of specific worker abilities with particular job demands, where the criteria for fulfilling these demands are determined by the company's operational needs or market forces. By doing so, management exercises control over the workforce, tailoring individual contributions to maximize productivity in accordance with business priorities.

The third and final principle involves the assignment of specialists from various professional backgrounds to oversee distinct productive functions. This practice laid the groundwork for the development of departments such as production planning and control, quality control, and the establishment of industrial regulations, among others, which are integral to industrial activity. These specialized departments further consolidated management's control over the production process, ensuring that every aspect of industrial operations was systematically regulated and optimized (Fleury and Vargas, 1983; Shou et al., 2022).

The limitations of Taylorist principles stem from their mechanistic conception of organizational structure and the work process. These principles assume that, regardless of contextual or environmental variations, standardized responses are both possible and desirable. This rigid framework diminishes the potential for innovative contributions from individuals outside of privileged corporate positions, who may otherwise enhance the efficiency of production or drive significant sectoral changes. By reducing workers' roles to narrowly defined tasks, Taylorism constrains the company's ability to adapt and respond to rapid political or economic transformations, resulting in diminished flexibility.

The rigidity of the organizational structure inherent to Taylorist management exacerbates these issues, as it limits improvisation, maneuverability, and responsiveness to unpredictable daily challenges. The excessive reliance on machines and pre-defined processes within this framework further reduces the capacity for creative problem-solving and adaptive responses. As a result, the system becomes vulnerable to disruptions and struggles to meet the demands of dynamic environments, where flexibility and innovation are crucial for sustained competitiveness and growth.

## 2.1 The role of industrial transformation in the modern world

The First Industrial Revolution, as interpreted by Hobsbawm (1999), must be understood as a period of accelerated growth driven by profound economic and social transformations. These transformations were rooted in the capitalist relationship between the owners of capital (money and means of production) and the owners of labor power—free workers—whose interactions were aimed at the valorization and accumulation of capital, as analyzed by Marx (1867). The revolution was the outcome of several key factors: changes in agricultural production designed to meet the needs of a rapidly growing population, the mass migration of rural peasants to urban centers where they became industrial workers, competition for control over colonial markets, and the rise of new production methods, most notably in the textile industry (Hobsbawm, 1999). These developments laid the groundwork for the capitalist system and fundamentally altered the socio-economic landscape, marking a critical juncture in the history of industrialization.

According to Ewen (1976), the second industrial revolution was marked by the establishment of the labor market and extended beyond the mere introduction of new methods for mass production. A pivotal development during this era was the emergence of the consumerist doctrine, which successfully manipulated individual desires and needs to align with the profit interests of industries. This process of conditioning individuals to prioritize the acquisition of goods and services as the fundamental purpose of existence permeated various aspects of society, including factories, politics, families, and everyday life.

Industrial revolutions represent pivotal moments in human history, radically altering our relationship with the world. These transformative periods are characterized by a confluence of innovations that revolutionize production processes, often leading to profound societal disruptions.

The effects of industrial revolutions extend beyond the realm of production, encompassing political, economic, social, cultural, and cognitive dimensions. These transformations have the power to reshape societies irrevocably. While capable of generating significant advancements and wealth, industrial revolutions can also exacerbate inequalities and social conflicts.

While the term "industrial revolution" is often used generically, it is possible to differentiate these transformative periods based on specific technological, economic, social, and political changes. By examining these underlying factors, we can gain a deeper understanding of the unique characteristics of each industrial revolution.

The Industrial Revolution, a period of transformative economic and social change, originated in Western Europe, with France, England, and Germany serving as pioneering nations. Beginning around 1780, these countries witnessed a remarkable acceleration in the productive capacity of their societies, fueled by the increasing production of goods and services. This era marked the consolidation of the capitalist accumulation process.

As noted by Hobsbawm (1999), the initial phase of the Industrial Revolution centered on the production of goods, particularly textiles and metal-mechanics. These industries employed relatively low-intensity technologies and primarily responded to existing demand for their products and services. To catalyze a more profound industrial revolution, however, a global expansion of trade and the establishment of mechanized workshops capable of producing large quantities of goods at reduced costs were essential. This combination of factors created a self-sustaining market for these goods, driving further industrial development.

At this juncture, England emerged as the first nation to initiate a process of industrialization, characterized by a confluence of technological and organizational innovations that represented a significant paradigm shift for the era. This transformation involved the establishment of various incentives and opportunities that facilitated the growth of manufacturing industries, particularly through the procurement of low-cost inputs from colonial territories.

Additionally, the availability of labor was bolstered by the migration of individuals from rural areas to urban centers, coupled with ongoing modifications to production methods that enhanced efficiency. The expansion of markets, particularly through the growth of extra-European frontiers, played a crucial role in this process. Colonies not only supplied raw materials but also served as markets for the finished goods produced in England. This intricate interplay of factors contributed to the emergence of a robust industrial economy, fundamentally altering the social and economic landscape of the time.

The First Industrial Revolution marked a significant transition characterized by the introduction of mechanical production systems powered by hydraulic and steam traction, primarily within the textile industry. This shift necessitated changes in the organization of work, as production became concentrated at specific physical locations. The demand for labor created a migration from rural areas to urban centers, fundamentally transforming England's economic structure from an agrarian and artisanal economy to an industrial one, driven by the manufacture of machinery utilizing steam power. This transformative process commenced in the mid-18th century and continued until the end of the 19th century.

In the early 20th century, a Second Industrial Revolution emerged, distinguished by a further evolution in production systems, notably through the implementation of Fordism. This phase introduced mass production techniques and a heightened division of labor. It was characterized by the widespread adoption of fossil fuels and electricity, which became integral to industrial operations. The Second Industrial Revolution was predominantly propelled by advancements in the chemical, electrical, and automobile industries, marking a new era of technological and organizational sophistication in manufacturing.

In the 1970s, a Third Industrial Revolution commenced, characterized by the integration of microelectronics and information technologies aimed at automating production and industrial processes. This revolution was marked by significant advancements in work organization, notably through the principles of scientific management articulated by Taylor et al. (1961). The incorporation of Taylorism into the framework of continuous improvement in production, as emphasized by Ohno (2018), played a pivotal role in shaping this era.

These developments naturally led to a gradual replacement of human labor on the factory floor, driven by the increasing reliance on scientific methodologies. The growing incorporation of a scientific component into industrial processes was underpinned by the extensive use of data and automation technologies. As a result, the Third Industrial Revolution not only transformed production capabilities but also fundamentally altered the dynamics of labor relations within the industrial sector, emphasizing efficiency and precision through technological innovation.

## 2.2 The fourth industrial revolution and Industry 4.0

The term "Industry 4.0" was first introduced at the Hannover Fair in Germany in 2011, representing an initiative by developed nations to reclaim their competitive share in the global industrial landscape, particularly in response to the rising influence of Asian countries in value-added manufacturing (FIRJAN, 2016). Schwab (2016) articulates that Industry 4.0, often referred to as "smart factories," facilitates the interaction between physical and virtual production systems on a global and flexible scale, potentially leading to innovative work practices.

Chancellor Angela Merkel emphasized the transformative nature of Industry 4.0, stating, "Industry 4.0 is the complete transformation of the entire sphere of industrial production through the fusion of technology and the internet with conventional industry" (European Parliament, 2015).

In a more detailed exploration of this concept, Hermann, Pentek, and Otto conducted a bibliometric study that cataloged various materials across five different databases in both German and English. Their research culminated in the following definition of Industry 4.0:

> Based on the results of the literature review, we define Industry 4.0 as follows: Industry 4.0 is a collective term for technologies and concepts for organizing the value chain. Within the modular structured smart factories of Industry 4.0, the SCP monitors physical processes, creates a virtual copy of the physical world and makes decentralized decisions. Through the IoT, the SCP communicates and cooperates with each other and with humans in real time. Through the IoS, both internal and inter-organizational services are offered and used by participants in the value chain (Hermann et al., 2015).

The authors also state that Industry 4.0 has four key elements in its composition. Table 1 provides a brief definition of these elements.

Table 1 shows that in Industry 4.0 there is a complete interaction between physical and virtual elements, with the aim of increasing production efficiency in the new industries. In addition, the elements also show us that there has been a major change in ways of working, with the integration of physical machines and the virtual world, in which people are increasingly being left out of production processes. On the other hand, according to the World Economic Forum (2020), the demand for Information Technology (IT) professionals, who are professionals with the requirements to work with the new technologies of industry 4.0, is increasing.

In Brazil, the advancement of Industry 4.0 has not yet reached the levels observed in other countries, as the nation remains primarily in the transition phase from Industry 3.0. FIRJAN (2016) indicates that a significant portion of the national industry is still moving from Industry 2.0 to Industry 3.0. This transition involves a shift away from traditional production systems reliant on assembly lines and electrical power toward more automated, robotics, and programming-based production systems.

According to the National Confederation of Industry (CNI, 2016), further development of Industry 4.0 in Brazil necessitates that companies begin integrating digitalization into their production and service delivery processes. A study conducted by CNI revealed that 42% of surveyed companies were unaware of the critical role that digital technologies play in enhancing industrial competitiveness. Furthermore, more than half of the respondents indicated that they do not employ any form of digital technology in their operations.

This context presents a considerable challenge for the implementation of Industry 4.0 in Brazil. While some companies are beginning to adopt technologies associated with Industry 4.0, a substantial number still need to embrace this paradigm shift. In light of these challenges, it is essential to engage in critical reflection and propose solutions that facilitate the integration of these technologies. FIRJAN (2016) identifies several key factors for discussion, including:

> (...) to obtain intelligent strategic policies, incentives and incentives from the government; to bring together entrepreneurs and industry managers with vision, boldness and a proactive attitude; to have technological development and the training of highly qualified professionals by academic and research institutions, preferably in close proximity to industry.

Incentive policies for Industry 4.0 represent a viable solution for the implementation of advanced technologies across various sectors. However, such initiatives must be executed thoughtfully and strategically, with a strong emphasis on investment in research and the integration of research institutions with the industrial, agricultural, and service sectors. Additionally, these policies should be designed to accommodate businesses of all sizes, ensuring that small and medium enterprises (SMEs) are not excluded in favor of large corporations that already possess the economic capacity to adopt digital technologies.

The Brazilian agricultural sector has begun to incorporate certain technologies associated with Industry 4.0, particularly within large farms and startups that offer services in this domain. In recognition of this potential, the Ministry of Agriculture, Livestock and Supply (MAPA), the Ministry of Economy (ME), the Ministry of Science, Technology and Information (MCTI), and the Brazilian Industrial Development Agency (ABDI) jointly launched a call for proposals for the Agro 4.0 Program in 2020[2].

The primary objective of the Agro 4.0 Program is to promote the adoption of Industry 4.0 technologies within agribusiness,

2 Brazilian Industrial Development Agency. Call for tenders No. 003/2020 agro 4.0: selection of projects to adopt and disseminate 4.0 technologies in agribusiness. Available at: https://agro40.abdi.com.br/SitePages/Layout/edital.aspx.

TABLE 1 Key elements of industry 4.0.

| Cyber physical Systems—CpS | Internet of Things (IoT) | Internet of Services (ioS) | Smart factories |
|---|---|---|---|
| These are systems that allow real operations to be connected to automated computing and communication infrastructures. | It is the network of physical objects, systems, platforms and applications with embedded technology to communicate, sense or interact with internal and external environments. | When the IoT network works perfectly, the data processed and analyzed together will provide with a new level of added value. | In smart factories, CpS will be used in production systems, generating significant gains in efficiency, time, resources and costs compared to traditional factories. |

Source: Own elaboration based on Hermann et al. (2015). Translation by FIRJAN (2016).

thereby enhancing efficiency, productivity, and cost-effectiveness in Brazilian agricultural practices. To achieve this goal, the program is designed to support companies or farms utilizing 4.0 technologies, which are categorized into four distinct groups.

Winners of the program will be awarded in each category, with a total of up to 14 projects eligible for recognition, as detailed in Table 2. To qualify, companies must actively implement 4.0 technologies and align themselves with the National Classification of Economic Activities. This initiative represents a crucial step toward fostering innovation and competitiveness within Brazil's agribusiness sector while addressing the need for equitable access to advanced technological resources.

One notable criticism of the Agro 4.0 Program pertains to the size and capacity of the companies eligible to participate. The program appears to favor firms that already possess substantial economic resources, thereby inadvertently excluding smaller enterprises that could also benefit from integrating Industry 4.0 technology concepts into their operations. A pertinent example is sustainable family farming, which plays a crucial role in feeding Brazilian society, contributing to ∼70% of the food consumed in the country. Despite its significance, this sector has yet to fully embrace digital technologies within its production processes and operational methodologies (Zoby et al., 2003).

Although the program faces these criticisms, it provides a valuable framework for reflecting on the application of disruptive technologies in sustainable family farming. The categorization of technologies by sector offers a constructive perspective for examining how these innovations can be leveraged effectively. In the subsequent section, we will explore various disruptive technological innovations, assessing their advantages and disadvantages within the context of sustainable family farming. This analysis will help illuminate the potential pathways for integrating advanced technologies into this vital sector, ultimately contributing to enhanced productivity and sustainability.

## 2.3 Disruptive technological innovations

With the advent of the Fourth Industrial Revolution, technological innovations have become increasingly integrated into our daily lives. For instance, the use of smartphones equipped with applications facilitates informed decisions regarding the application of organic products in agricultural production. Such technologies exemplify the new digital technologies associated with Industry 4.0, which are fundamentally reshaping the way we conduct activities—both professionally and recreationally. These innovations are often categorized as disruptive innovations due to their transformative potential.

TABLE 2 Distribution by category of awarded projects.

| Category | Value | Number of winners |
|---|---|---|
| Category 1 | R$ 300.000,00 | Four projects |
| Category 2 | R$ 300.000,00 | Four projects |
| Category 3 | R$ 300.000,00 | Four projects |
| Category 4 | R$ 600.000,00 | Two projects |

Source: Own elaboration based on Agro 4.0: Adoption and Diffusion of Technologies in Agribusiness (2020).

The concept of disruptive innovation was pioneered by Clayton Christensen in his seminal works *The Innovator's Solution* and *The Innovator's Dilemma*. Christensen builds upon Joseph Schumpeter's notion of creative destruction, which describes the continuous process of dismantling old structures while simultaneously fostering the emergence of new ones, akin to an industrial mutation (Schumpeter, 1961). In the context of disruptive innovations, while the applications may be simpler in nature, the effects on market structures can be comparably profound, mirroring the consequences of creative destruction.

Disruptive innovations introduce novel solutions to various market challenges, particularly addressing the needs of non-traditional consumers who may have been overlooked by existing products or services (Christensen et al., 2006). This dual capacity for simplicity in application and significant market impact underscores the pivotal role that disruptive technologies play in shaping contemporary economic landscapes and consumer behaviors.

According to Nogami (2018), "creative destruction involves disrupting the market through innovative products and processes, while disruptive innovation focuses on variations in demand requirements." This distinction is further elucidated by the author's examination of the characteristics inherent to both perspectives: innovations associated with creative destruction tend to be radical, whereas disruptive innovations are typically incremental. Nogami also notes the similarities between the two concepts, particularly their shared capacity to "destabilize dominant systems such as monopolies, oligopolies, and large, established companies."

Table 3 presents various disruptive technologies that could be leveraged in sustainable family farming, thereby enhancing its resilience and viability. However, it is crucial to approach the integration of these technologies with caution, ensuring that their implementation does not inadvertently subject family farms to the dominance of monopolies, oligopolies, and large corporations. Instead, the focus should also encompass strategies that empower families, fostering their independence and autonomy.

TABLE 3 Disruptive technologies in agriculture by segment.

| Technology | Positive | Negative |
|---|---|---|
| **Input segment** | | |
| 3D printing | Accelerated product development; reduction of the design-manufacturing cycle; easy production of parts and tools | Increase in waste for disposal; production of anisotropic parts; piracy; brand and quality changed |
| Bioinsumos | Control of unwanted organisms in production; reduce environmental impact; increase the performance of seeds, soil and plants; biofertilizers | New environmental problems; registration and patenting; access and cost; production and knowledge |
| Seeds | Increased seed resistance to viruses and climatic variations; greater production efficiency; collaborative seed production; open patenting of genetic resources | Loss of seed varieties; dependence on the use of modified seeds; they can absorb herbicides or pesticides, causing possible damage to health and the environment |
| **Primary segment** | | |
| Internet of things and for things | Increased efficiency in the use of resources; increased productivity; logistical efficiency; the equipment will be able to use its environment comprehensively and act autonomously | Breach of privacy; threat to people's safety in the virtual world; consequences of a possible "*Pearl Harbol* Digital"; loss of jobs in the countryside; |
| Exoskeleton | Contributing to weight and strength reduction for rural workers; increased productivity in jobs that require strength; avoid diseases caused by excess weight | Muscular atrophy; posture problems over time; increased cardiac and energetic effort |
| **Secondary segment** | | |
| Food production | Reducing waste and increasing profitability; automation and dynamic information exchange; digitalization of production chains and demand | Technological dependence |
| Drones | Application of natural herbicides; application of biological agents; production mapping | High prices for small producers; dependence on companies that apply this type of technology; unemployment for professionals who don't master digital skills |
| Sensors | Monitor the weather; cost reduction; monitoring unwanted organisms | Technological dependence |
| **Tertiary segment** | | |
| Big data | Faster and better decisions; open data for innovation; reducing costs | Loss of work; privacy concerns; confidence in the data |
| Ubiquitous computing | Greater economic presence of disadvantaged populations, located in remote or underdeveloped regions; access to knowledge, greater employment and changes in the way people work; expanding the size of the market. | Walled gardens (limited environments for authenticated users only) do not allow full access to some countries. |
| A supercomputer in your pocket | Greater economic presence of disadvantaged populations, located in remote or underdeveloped regions; access to knowledge, greater employment and changes in the way people work; expanding the size of the market. | Environmental impact of production and disposal |

Source: Elaboration based on Schwab (2016) and Agro 4.0: Adoption and Diffusion of Technologies in Agribusiness (2020).

In this context, government organizations play a pivotal role in the development and dissemination of disruptive innovations. Their involvement is essential not only for facilitating access to these technologies but also for implementing supportive policies and programs that prioritize the needs and sustainability of family farms. By doing so, they can help create an environment conducive to innovation while safeguarding against the potential monopolistic tendencies that often accompany technological advancements.

The integration of disruptive technologies in agriculture offers numerous advantages across the four segments outlined in this paper. These benefits range from alleviating physical labor—an essential aspect of technological revolutions—to facilitating entry into the virtual marketplace. The adoption of disruptive innovations within family farming enables enhanced efficiency in production processes, risk monitoring, and the implementation of environmentally sustainable solutions.

Moreover, family farmers can gain access to both national and international markets through digital platforms, utilizing computers, tablets, or smartphones with internet connectivity. This connectivity not only enhances their operational capabilities but also brings them closer to consumer groups actively seeking specific products.

However, despite the myriad positive aspects associated with disruptive innovations, a strategic plan is imperative for their effective application in family farming. This plan should emphasize collaboration among farmers, society, government, and research institutions. The objective is to co-develop these technologies in a manner that empowers family farmers, ensuring they do not become overly dependent on the technology itself or on its suppliers. By fostering a collaborative approach, the agricultural community can harness the full potential of disruptive innovations while maintaining independence and resilience in the face of market fluctuations and technological changes.

## 2.4 Sustainable rural development and family farming

Reflecting on the impacts of Industry 4.0 on sustainable rural development, particularly concerning family farming, is crucial

in understanding the evolving dynamics of agricultural practices. Family farming, characterized by its historical reliance on low technology and intensive labor, is at a crossroads where the integration of advanced technological solutions could redefine its future (Buainain, 2007).

Sustainable rural development encompasses a complex array of interrelated factors. According to Schneider (2007), studying development involves a thorough examination of the social processes enacted by diverse human groups, which result in significant transformations in nature, physical and social spaces, and territorial configurations. This multidimensional process encompasses the adaptation and adjustment of production methods while simultaneously transforming societal norms and values.

The configurations inherent in these processes possess the capacity to generate surpluses and catalyze broader development pathways. Since the 1990s, the state's role has been pivotal in shaping public policies that are intricately linked to rural areas, particularly with regard to family farming (Schneider, 2007, p. 12). Such policies aim to foster environments where family farmers can enhance their productivity and sustainability, creating a balanced framework that supports economic viability alongside ecological integrity.

As we consider the integration of Industry 4.0 technologies—such as data analytics, automation, and the Internet of Things (IoT)—into family farming, it is essential to acknowledge both the opportunities and challenges that arise. On one hand, these technologies can empower family farmers to optimize their production processes, improve resource efficiency, and make informed decisions that contribute to sustainability. On the other hand, there is a risk that such integration may lead to dependency on external technological solutions, potentially undermining the autonomy and traditional knowledge of family farmers.

In this context, the influence of state policies becomes increasingly important. Effective public policies must promote not only the adoption of innovative technologies but also the empowerment of family farmers. This involves ensuring access to training, resources, and support systems that facilitate the integration of technology without compromising the foundational principles of sustainable agriculture. By fostering collaboration among government entities, research institutions, and farming communities, we can create a holistic approach that leverages Industry 4.0 advancements while promoting resilience and sustainability in family farming practices. Ultimately, reflecting on these dynamics is essential to shaping a future where family farming can thrive in harmony with sustainable rural development goals.

The discussion on rural development is sustained as an alternative and opposition to agribusiness practices. From an environmental point of view and with criticism of the effects brought about by the green revolution, its technological packages and their environmental effects, other productive alternatives are being consolidated, linked to technical-productive models called alternative, ecological, organic, regenerative, agroecological and other nomenclatures (Almeida, 1999; Ehlers, 1996).

At this point, the ability of these types of models to propose new socio-technical configurations is fundamental, bringing new formats and production models that have become a possible horizon for sustainable rural development.

Given this scenario, it is possible to imagine that the future of rural development will be strongly linked to modernization and technology, especially when we talk about contexts such as family farming, where the basis of profitability is directly linked to agricultural production. In this sense, when we start a debate on technological innovation and agriculture 4.0 (in the context of industry 4.0), we first need to overcome the stereotypical conception of family farming that we still see today.

Although it is highly diverse (Schneider, 2009), we can understand Family Farming, henceforth referred to as FA, as the integration of family, production and work (Wanderley, 1996), as a counterpoint to the industrial logic of so-called Modern Agriculture—AM, or capital-intensive agriculture. CA is based on smallholdings with a wide variety of crops, managed by local owners and staffed essentially by family members (Lamarche, 1993). It is the family's main financial source, retaining the population in rural areas and therefore being one of the main factors responsible for maintaining the local culture and market. While AM is based on medium and large properties, essentially based on monoculture, managed by owners or business groups from outside the region, with employees and professionals generally hired from elsewhere, focused on trading their products in large markets (e.g., exports) and with intensive use of capital and technology.

This format of family-based sustainable rural development can be found in various countries, with different forms of support and local importance, especially in Asian countries such as China and India, African countries such as Ethiopia, and even developed countries such as the United States, Canada, France and Japan. According to the Food and Agriculture Organization of the United Nations (FAO), FA is responsible for a third of the food produced in the world and it is estimated that around 500 million families are in this economic regime. This system cannot be understood generically as a backward sector (mainly technologically and economically), since it is responsible for the production of basic products in the production chain (mostly food) and under an almost subsistence logic. Such an understanding ignores the real role of family farming in the world and in Brazil.

Family farming plays a major role in Brazil, representing around 10 million families and, according to data from the National Confederation of Workers in Family Farming in Brazil (2021), is responsible for 70% of the food that reaches the Brazilian population. The term is defined by law 11.326 of 2004 and states that a family farmer must meet four criteria in order to be legally recognized:

> I. does not own, in any capacity, an area larger than four fiscal modules; II. uses predominantly their own family's labor in the economic activities of their establishment or enterprise; III. has a minimum percentage of their family income originating from the economic activities of their establishment or enterprise, as defined by the Executive Branch; IV. runs their establishment or enterprise with their family (Brazil, 2006). *NOTE: A fiscal module is between 5 and 110 hectares.*

Therefore, a family farmer includes all farmers who carry out rural practices in compliance with the four legal criteria, as well as people from various sectors, such as: agrarian reform settlers (belonging to the Landless Movement—MST), quilombolas, indigenous people, foresters, fishermen and aquaculture producers.

Contrary to the importance of family farming, there is a continuous distancing from the process of modernization and technology, due to the very low level of schooling in the countryside, the lack of connectivity and limited access to credit. Also according to research by the National Confederation of Workers in Family Farming in Brazil (2021), if the country invested in expanding connectivity in the countryside (digital inclusion), the gross value of agricultural production in the country could increase by up to R$78 billion. However, the figures published by the Brazilian Institute of Geography and Statistics (2017) show that only 14% of family farms have access to agricultural mechanization.

Despite this national reality, AF is responsible for an annual turnover of 52.2 billion (2018), well-above AM's 30 billion in the same year. It would therefore be natural to infer that ML has less planted land and that its efficiency of use was or still is higher in ML than in FA. However, despite being present in 77% of all rural establishments, FA occupies only 23% of the country's cultivated areas. Its turnover in relation to the area occupied demonstrates its strength and importance for national and world food, even with the current poor technologies applied (Reichert et al., 2015).

The importance and diversity of family farming in Brazil requires the adoption of differentiated policies adapted to the different configurations. Even taking into account the risks of unemployment and other impacts on the social structure. This opens up a discussion about the innovative technologies that can and should be applied to family farming (Valdiero et al., 2015), the so-called appropriate technologies. As well as evaluating trends in the implementation of precision farming techniques, commonly used in PA, adapted to sustainable agriculture schemes (Hassall, 2010).

A foundational step in this discourse is to comprehend the extent to which technology serves as a cornerstone for decision-making, planning, and the implementation of optimal production techniques and processes within family farming. While technological advancements are undeniably crucial, it is imperative to recognize that rural development is not exclusively determined by these factors.

Contemporary rural development is significantly influenced by external factors, with national infrastructure playing a particularly pivotal role. The integration of technology into rural areas faces two primary infrastructure challenges: universal access to electricity and connectivity. As highlighted by Souza Filho et al. (2004), the average availability of electricity in Brazilian family farming establishments is a mere 38%. Moreover, the quality of this electricity, often supplied through single-phase networks prone to frequent interruptions, is insufficient for many production and technological applications.

According to the 2017 Agricultural Census, released in 2019 by the Brazilian Institute of Geography and Statistics (IBGE), of the 5.07 million rural establishments in Brazil, 3.64 million do not have internet access, or 71.8% of properties. Of the 5 million rural establishments, <28% have an internet connection and, of these, only 46% have broadband. Brazil's strategic growth, with no direct impact on nature, depends directly on bringing the internet to rural areas. In this scenario, a positive trend can be considered. According to data from Embrapa (2020), between 2006 and 2017 there was a 1,900% increase in access to the internet by rural producers, mainly due to smartphones.

In addition to infrastructure barriers, we can highlight some other important points when we think about the difficulties in implementing technology in family farming. These are

- Lack of economic protection mechanisms to cushion the impact of negative production results, leading to resistance to technological innovations on the part of producers. Rural credit in Brazil has always been channeled mainly toward medium and large farmers and has ended up excluding family farmers from technological insertion;
- Lack of interest from technology manufacturers and suppliers: family farming is not considered a relevant audience for agricultural technology manufacturers and suppliers. The innovations and technological tools that promise to make agricultural systems more efficient, sustainable and economically more profitable are not even designed for small producers to access. The very logic behind the development of these technologies is that the larger the farm and the scale of production, the greater the volume of data that can be collected and used in technological development;
- The need for a large investment: in order to meet the different needs of the field, a broad integration of different technologies and processes is necessary for the results to be effective. In other words, the investment in acquiring and implementing digital technologies in production tends to be extremely high and unfeasible for small producers;
- Low instruction level of rural producers: In many countries, information on agricultural innovations is provided by government extension agencies. In Brazil, given the social profile of many family farmers, in particular their low level of education, the use of conventional technical material is not very effective. As the traditionally important official extension services have been dismantled in recent decades, the issue of disseminating information and training to use it is a bottleneck for the development of family farming in the context of Agriculture 4.0.

To reverse the current scenario of limited technology adoption in rural areas, the federal government must prioritize a comprehensive plan for democratizing these technologies. The challenge lies not only in the availability of suitable technology but also in the lack of adequate financing and dissemination mechanisms to make family farming a sufficiently attractive market segment for technology and service providers.

Strengthening relationships and commitments between family farmers (end-users) and researchers and their institutions is crucial. This collaboration can foster the development and adaptation of technologies that address the specific needs of small-scale agriculture.

The current reality underscores the importance of government support and research institution involvement in facilitating the

inclusion of family farming in the technology landscape. By providing the necessary resources and expertise, these entities can play a pivotal role in bridging the digital divide and empowering family farmers to leverage technological advancements for sustainable and profitable agricultural practices.

### 2.4.1 Institutions, innovation, and sustainability

As emphasized by Veiga (2002) and Abramovay (2004), family farming plays a vital role in bolstering local economies at various levels. This capacity stems from the innovative nature of family farmers and their ability to effectively interact with existing institutional networks. Such interactions facilitate the creation of value-added products, reduce logistical costs, and stimulate multi-level economic dynamics.

These authors highlight the inherent capacity of family farmers to generate innovative processes. The constant need to adapt and survive in often challenging environments has fostered a culture of innovation within this sector. Consequently, the social and productive diversification of territories can be attributed, in part, to the innovative and productive capabilities of family farmers (Schneider, 2007, p. 19).

Schneider (2007) analysis of Veiga's work underscores the critical role of rural entrepreneurship in driving local economic development. The demand for products and services generated by family farmers within a specific territory, considering their average scale, can create systemic dynamics that stimulate the circulation of wealth and foster development.

Abramovay (2004) further emphasizes the importance of factors such as collaboration, cooperation, reciprocity, and solidarity within proximity economies. These factors facilitate innovation processes by fostering collaborative dynamics and encouraging joint projects.

### 2.4.2 *On the limits of incorporating* innovation

Analyzing development processes requires a comprehensive understanding of both their potential and limitations. In rural areas, existing power relations and traditional modes of domination can hinder progress by perpetuating the status quo. To counter these obstacles, it is imperative to expand democratization processes and increase direct participation in decision-making, thereby limiting the influence of mediating groups and elites (Souza, 2021).

Navarro (2001) highlights the presence of conservatism among social actors in rural areas, coupled with a lack of technical capacity and human resources capable of generating innovative proposals for profound change. The author attributes part of this conservatism to the inherent instability of the organizational base within these communities.

Wilkinson (2006) points to a series of characteristics of family farmers and their organizations as limits to the development of innovative processes in rural development, among which the following stand out: the low level of instruction of farmers and their organizations' teams; the limited capacity of local markets to absorb surpluses; the scale required by traditional marketing networks; the issue of intellectual property rights and the danger of private appropriation of the results of innovations; the continuity of compensatory public policies; and the incorporation of the new rurality into public policies.

The integration of family farmers into agri-food or agri-industrial marketing chains, or even the creation of new ones, necessitates careful consideration of its potential social implications. Given the inherent inequalities in market entry conditions, it is crucial to examine these factors alongside the role of technological innovations and food chains in rural development processes.

In the current context, family farming faces increasing demands related to food security, environmental sustainability, and fair production methods. Wilkinson (2006) emphasizes the need for family farmers to develop skills that enable them to consolidate new markets through consumer interaction, the organization of socio-technical networks, and the establishment of short production and consumption chains aligned with consumer demands.

Schneider (2007, p. 29) highlights the remarkable capacity of family farming to successfully respond to the flexible demands of modern markets. This adaptability is rooted in their ability to innovate through experimentation (learning-by-doing) and collective learning facilitated by tacit knowledge.

## 3 Discussion

This paper explores the profound transformations brought about by the industrial revolutions across societies, economies, production systems, cultures, and the rural world. By examining the key disruptive innovations emerging in rural areas, the analysis aims to position these advancements within the context of sustainable rural development, where family farming plays a pivotal role. Industry 4.0, characterized by the convergence of physical and virtual systems, offers greater flexibility in production within a globalized environment. This paradigm shift introduces new forms of production that can generate novel work opportunities while also presenting unique challenges.

To illustrate the potential impact of disruptive technologies, this paper examines relevant examples across various sectors. By considering both the positive and negative aspects of these innovations, the analysis provides a comprehensive understanding of their implications for rural development. Given the current configuration of Brazilian agriculture, agribusiness stands out as the most dynamic sector for incorporating Industry 4.0 technologies. This is evident in the various programs, such as the Agro 4.0 Program, that actively promote the adoption of these innovations.

The Brazilian Agricultural Research Corporation (EMBRAPA) has undertaken commendable initiatives to facilitate the integration of technology into family farming. Through its research and development efforts, EMBRAPA has developed innovative technological tools aimed at boosting agricultural production among small-scale farmers. These tools encompass a wide range of technologies, including artificial intelligence, machine learning, automation and robotics, blockchain and cryptography for traceability, and the Internet of Things (IoT). The adoption of these technologies, such as sensors, drones, applications, software, management systems, satellite images, tractors, sprayers, and automatic harvesters, has the potential to transform traditional

rural areas. By harnessing the power of these tools, family farmers can enhance their productivity, efficiency, and sustainability.

In forest management, the adoption of digital technologies has changed the reality of the activity, making it easier to carry out stages, reducing effort and speeding up and improving the accuracy of area mapping processes. Drones, for example, provide detailed knowledge of the forest from an aerial perspective, making it possible to carry out semi-autonomous inventories using high-precision tools and algorithms for automatic segmentation and geolocation of trees. Together with other automated technologies, such as the Digital Forest Exploration Model (Modeflora) and Lidar (Light Detection and Ranging), this equipment is part of what is known as "forest management 4.0", a new concept in forestry production based on the automation, generation, transmission and processing of precise data in the activity.

Another innovative research project, funded by the São Paulo State Research Foundation (FAPESP), uses drones to count cattle; the methodology could contribute to monitoring animal weight and health. Swamp (Smart Water Management Platform) uses the Internet of Things (IoT) to create an intelligent water management platform for precision irrigation, in partnership with the European Union and coordinated by the Federal University of ABC (UFABC).

Beyond the ongoing research initiatives, several other projects, some nearing completion with successful proof of concept and prototype testing, are poised to have a significant impact on key production chains, including fruits and vegetables, soybeans, coffee, cotton, dairy farming, and viticulture. These innovations have the potential to benefit family farms, provided that the necessary infrastructure is in place. The success of these projects underscores the feasibility of digital inclusion in rural areas, demonstrating that with appropriate government and institutional support, family farmers can effectively adopt and leverage advanced technologies.

## 4 Conclusion

While the challenges facing family farming are multifaceted, the issue of technology adoption should not be overlooked. Given the paradigm-shifting moment in production systems, particularly agri-food systems, due to the convergence of disruptive technologies, technological innovation offers significant potential for family farmers.

Recognizing the inherently innovative nature of family farming, its capacity to incorporate various technologies and adapt its processes can contribute to more dynamic and sustainable rural development. This involves establishing multi-level networks that foster collaboration among various organizations.

To achieve this, it is imperative to dismantle existing power relations and modes of domination within Brazilian agriculture. Additionally, public policies must evolve beyond compensatory measures to actively support the development of family farming's innovative potential.

Promoting democratic processes that encourage the participation of family farmers, providing training and education for farm managers, and strengthening the role of support institutions are essential steps. Furthermore, given the current limitations of state-centric public policies, exploring alternative mechanisms to ensure autonomy and continuity in policy implementation is crucial.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

GA: Writing – review & editing.

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## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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# Crossing digital borders: technology in the migration process across the United States, Mexico, Honduras, and Chile

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This study examines the role of technology in migration processes across the United States, Mexico, Honduras, and Chile, with a focus on how technological tools are used primarily for control and management, and to a lesser extent, for facilitating integration. Through a qualitative methodology, including a comprehensive review of gray literature, this research analyzes the deployment of technologies by governmental and non-governmental institutions. Key findings reveal significant disparities in technological implementation, with the United States leading in advanced surveillance and control technologies, including biometric systems, artificial intelligence, and mobile applications like CBP One. In contrast, Mexico and Chile employ more limited technological tools, with Chile showing an emphasis on social inclusion through the Migrapp app. Honduras, on the other hand, lacks significant technological infrastructure for migration governance. The study highlights the risks associated with privacy invasion, surveillance, and social exclusion, particularly in the U.S, and calls for the responsible design and use of technology to ensure the protection of migrants' rights and to foster inclusion rather than exacerbate inequalities.

KEYWORDS

**technology, migration, social inclusion, social technology, technological devices**

## 1 Introduction

Migration movements are complex and multidimensional phenomena, influenced by various economic, political, social, and environmental factors (World Bank, 2022). Today, migration not only transcends geographical borders but also includes both national and transnational migration (Pripoaie et al., 2022), which has added to its complexity. This situation directly affects migrants' access to essential services such as healthcare and education, while also raising concerns about the protection of their human rights. Contemporary migration not only transforms the lives of those who migrate, but also reshapes the social dynamics of host societies.

Migrants are perceived in different ways: in some cases, they are seen as valuable contributors to economic and cultural diversity, while in others, they are perceived as a threat to social cohesion and national identity. Additionally, migration exacerbates pre-existing inequalities related to class, gender, ethnicity, and other social factors, redefining social categories and generating new meanings within the context of human mobility.

To understand the complexity of modern migration, it is essential to examine the power structures that underlie both individual and collective experiences in the migration context. As Foucault points out, power relations not only influence the creation of discourses and the formation of identities, but also operate through mechanisms of control and exclusion that regulate migration flows (Íñiguez Rueda, 2003; EDRi, 2024).

These dynamics manifest in the regulations, institutional practices, and devices of host societies, which can either promote the inclusion or exclusion of migrants, directly impacting public policy and social dynamics.

The COVID-19 pandemic has intensified many pre-existing crises, exacerbating food insecurity, violence, and environmental degradation, leading to an increase in forced migration (United Nations Development Programme, 2023). This context has highlighted the fragility of social and political systems, underscoring the urgent need to design effective policies to manage this forced migration. At the same time, the world is undergoing a profound technological and digital transformation, which presents both opportunities and challenges in the migration arena. Technological tools have emerged as "social technologies," designed and implemented to facilitate the inclusion of migrants, maintain connections between countries of origin and destination, and provide access to social services, labor information, and support networks. However, the use of these technological tools does not guarantee successful inclusion. While tools like mobile phones, the Internet, and applications like WhatsApp can mitigate isolation, they can also foster exclusion through criminalization, xenophobia, and the reinforcement of prejudices (Pérez Díaz and Aguilar Pérez, 2021; Cabalquinto, 2023).

Moreover, emerging technologies such as biometric devices and artificial intelligence algorithms are increasingly being used at migration borders, which has led to increased discrimination and exclusion based on "race" and other factors (United Nations High Commissioner for Human Rights, 2020). Therefore, it is crucial that technological tools used in migration processes are regularly reviewed to ensure their alignment with human rights, as highlighted by experts and international organizations (Gelb and Krishnan, 2018). However, significant gaps remain in understanding how these technologies affect migrants and host societies.

In this context, this research proposes a comprehensive review of the use of technological tools in migration processes in some countries of the Americas (the United States, Mexico, Honduras, and Chile), with a special emphasis on Latin America. The aim is to identify the strategies and technological devices used by governmental and non-governmental institutions to facilitate or regulate migration, and to analyze the potential benefits and risks these technologies pose to migrants.

This study also seeks to address the existing gaps in the scientific literature on the interaction between migration and technology, providing valuable information that could influence the development of fairer and more humane policies and technological tools. By examining the role of these tools, the study aims to contribute to rethink the design of migration technologies and policies that promote a more inclusive process respectful of human rights.

# 2 Methodology

This study was conducted using a qualitative methodology, employing a literature review process as the foundation for thematic analysis (Braun and Clarke, 2006). Qualitative research is a robust approach to explore complex phenomena and obtaining an in-depth understanding (Onwuegbuzie et al., 2012). Within this methodological framework, the literature review plays a crucial role in identifying, synthesizing, and evaluating a body of literature (Turyahikayo, 2014; Braun and Clarke, 2006). Subsequently, a thematic analysis was conducted to identify, analyze, and interpret recurring patterns or themes within the data set (Lochmiller, 2021).

## 2.1 Gray literature review process

Gray literature, including theses, news media archives, and technical reports, plays a pivotal role in research on technology. Its value stems from offering current information and unique perspectives that are often missing in traditional academic publications due to lengthy peer-review and publication timelines (Paez, 2017). The inclusion of gray literature is especially relevant in areas like security, where open sources may be limited, and in providing exclusive, recent data.

To harness the benefits of gray literature, a comprehensive review was conducted using Google as the primary search engine. Google was selected for its accessibility and widespread use in the countries analyzed, as it indexes diverse content, such as news, technical reports, government studies, and unpublished academic documents. Through Google, a wide range of updated and direct sources—often unavailable in traditional academic repositories—were accessed, including institutional publications, reports from international organizations, legislative documents, and news media. Google's ease of use and availability make it a key tool across multiple regions (StatCounter, 2024). An analysis by country shows that Google dominates in Chile, Mexico, the United States, and Honduras, with over 90% market share in each, reinforcing its role as the preferred platform for accessing information in these regions (StatCounter, 2024).

### 2.1.1 Keywords and search phrases

keywords: "technology and migration," "technological devices and migrants," "migration management systems," "migration surveillance," "Honduras, Mexico, Chile, United States".

Search Phrases in Spanish: "tecnología en migración Honduras OR México OR Chile OR Estados Unidos" "dispositivos tecnológicos y migración Honduras OR México OR Chile OR Estados Unidos" "sistemas de gestión de migración Honduras OR México OR Chile OR Estados Unidos" "vigilancia en migración Honduras OR México OR Chile OR Estados Unidos".

Search Phrases in English: "technology and migration Honduras OR Mexico OR Chile OR United States" "technological devices and migration Honduras OR Mexico OR Chile OR United States" "Migration management systems Honduras OR Mexico OR Chile OR United States" "migration surveillance Honduras OR Mexico OR Chile OR United States".

### 2.1.2 Inclusion criteria: document types and dates

The study includes news articles, technical reports, specialized blogs, and conference papers, emphasizing gray literature due to its timely and practical insights. These documents often cover real-world applications of technology in migration governance, offering perspectives crucial for the research's practical orientation. Documents published between 2019 and May 31, 2024, were included, reflecting rapid technological advancements in AI, big data, and digital platforms that have transformed migration governance. The COVID-19 pandemic and climate-induced migration have also driven the adoption of technologies for border control and migrant assistance during this period.

### 2.1.3 Inclusion criteria: countries of analysis

This study comprehensively explores the interplay between migration and technology, focusing on the United States, Mexico, Honduras, and Chile. These countries were chosen due to their distinct roles in migration dynamics and diverse technological landscapes shaped by unique economic, social, and political contexts. This selection allows for the examination of various American realities across different development levels.

The United States, as one of the most technologically advanced nations and the world's largest recipient of migrants, plays a critical role in shaping global migration dynamics. Despite its strong economy, marked by a high GDP and a culture of innovation, the country grapples with deep socioeconomic inequalities and political polarization, particularly around migration issues (International Monetary Fund (IMF), 2024). The U.S. employs cutting-edge technologies, including advanced surveillance systems, artificial intelligence, and data analysis, primarily at its southern border with Mexico to monitor migrants from the Northern Triangle countries (El Salvador, Honduras, and Guatemala) (Capps et al., 2017, 2019). These technologies significantly impact migrant routes, strategies, and decision-making processes. Moreover, organized crime and human trafficking continue to pose serious challenges within this migration landscape (Have et al., 2023). As the 2024 presidential elections approach, debates around immigration policy have intensified, focusing on how to balance national security with humane migration policies (AP News, 2024). These discussions reflect the broader socio-political landscape, where immigration remains a deeply divisive issue, influencing both domestic politics and international relations (AP News, 2024).

Mexico presents a complex scenario as both a major source of migrants to the U.S. and a keytransit country for Central and South American migrants (Basok and Candiz, 2020). Despite having one of the largest economies in Latin America, with the second-highest GDP in the region, high inequality, widespread poverty, and a significant informal sector drive many to migrate (Preker et al., 2021). Political instability and corruption exacerbate these challenges (Zepeda, 2014). Additionally, severe crime and violence, largely due to drug cartels, make migrants vulnerable to extortion, trafficking, and other dangers. While technology plays a crucial role in communication, risk management, and accessing information, the digital divide in Mexico limits its full potential (Coria and García-García, 2022a,b). These factors make Mexico a critical case for studying migration, technology, and socio-economic disparities.

In contrast, Honduras—predominantly a country of origin—faces high rates of emigration to the U.S. due to socioeconomic challenges and climate change, and it has one of the lowest GDPs in the region (World Bank, 2022; Have et al., 2023). Additionally, Honduras' strategic location in Central America has made it a critical transit route for migrants from countries like Venezuela, as well as a hotspot for organized crime and drug trafficking (UNOCHA, 2022). Technology is crucial for Honduran migrants to maintain family connections and send remittances. However, the country struggles with limited access to technology and poor digital literacy, which increases migrants' vulnerability to risks such as human trafficking (Organización Internacional para las Migraciones, 2023). These technological deficiencies hinder effective migration governance and human rights protection, limiting the potential for technology to safeguard migrants throughout their journeys.

Chile has emerged as a destination country, attracting migrants from neighboring nations due to its economic stability and steady growth over recent decades (United Nations Development Programme, 2023). With one of the highest GDP per capita in Latin America, strong export sectors, and a growing focus on technology and innovation, Chile presents an attractive destination for migrants seeking better opportunities (Marca Chile, 2022). However, Chile also faces sociopolitical challenges, such as increasing criminality, social polarization, and corruption (Solimano, 2012). The country's visa exemption policies for skilled migrants, investors, and certain nationalities facilitate migration but have also led to increased xenophobia and discrimination, particularly with the influx of Venezuelan immigrants. These issues are now central to public and governmental discourse (United Nations Development Programme, 2023). Chile's advanced technological infrastructure offers a unique environment to study how technology interacts with migratory processes, making it an important case for understanding the intersection between migration and technology.

### 2.1.4 Technologies included by the inclusion criteria

The research focuses on technologies aimed at adult migrants, without gender distinction, and implemented by governments and civil society. These technologies target different migration phases: preparation, the migratory act, settlement, and integration (Tizón et al., 1992). They are examined for their impact on enhancing migrants' experiences and outcomes.

### 2.1.5 Exclusion criteria

The study excluded documents that were incomplete, inaccessible, or behind paywalls, as well as scientific articles and books. The focus is on gray literature to capture practical insights into migration technology, which are often more immediate than those found in academic publications. Additionally, documents that centered on migration governance through social networks or informal surveillance platforms were excluded, to maintain a specific focus on formal technological interventions implemented

by governments and civil society. Furthermore, technologies designed for and implemented with minors were excluded from the study. This decision was made based on ethical considerations and human rights principles, as these technologies should only be applied to adults with informed consent (United Nations Population Fund (UNFPA), 2023).

## 2.2 Document selection process

During the initial review of titles, researchers identified 1,255 documents retrieved from the search. The document selection process began with three researchers conducting the initial search together, which yielded a total of 1,255 documents. From this pool, the researchers collaboratively reviewed and preselected, based on title, abstract, and consensus regarding the relevance to the research objectives and the inclusion and exclusion criteria. After this collective revision, a total of 110 documents based were preselected. To ensure the quality of the final selected documentation, the three researchers independently reviewed the abstract of each pre-selected document (110 documents). The following criteria guided their individual and evaluation:

- Clarity and precision of information: Reviewers assessed whether the information presented was clear, concise, and accurate.
- Relevance and applicability to the research: Reviewers analyzed whether the document's content was pertinent and applicable to the research objectives.

Following individual reviews, the researchers identified documents that were unanimously included or excluded. Any discrepancies in document selection were resolved through discussion and consensus among the reviewers. This process fostered a dialogue that facilitated well-reasoned and collaborative decision-making, having in mind the objectives, inclusion and exclusion criteria. See Figure 1 to obsere the dcument selection process.

### 2.2.1 Quality of the selected sources

Finally, and related to the quality of the gray literature sources, used in this research on migration and technology reveals a notable diversity of origins, each with varying levels of quality and credibility (see Table 1), which is crucial for constructing a solid and

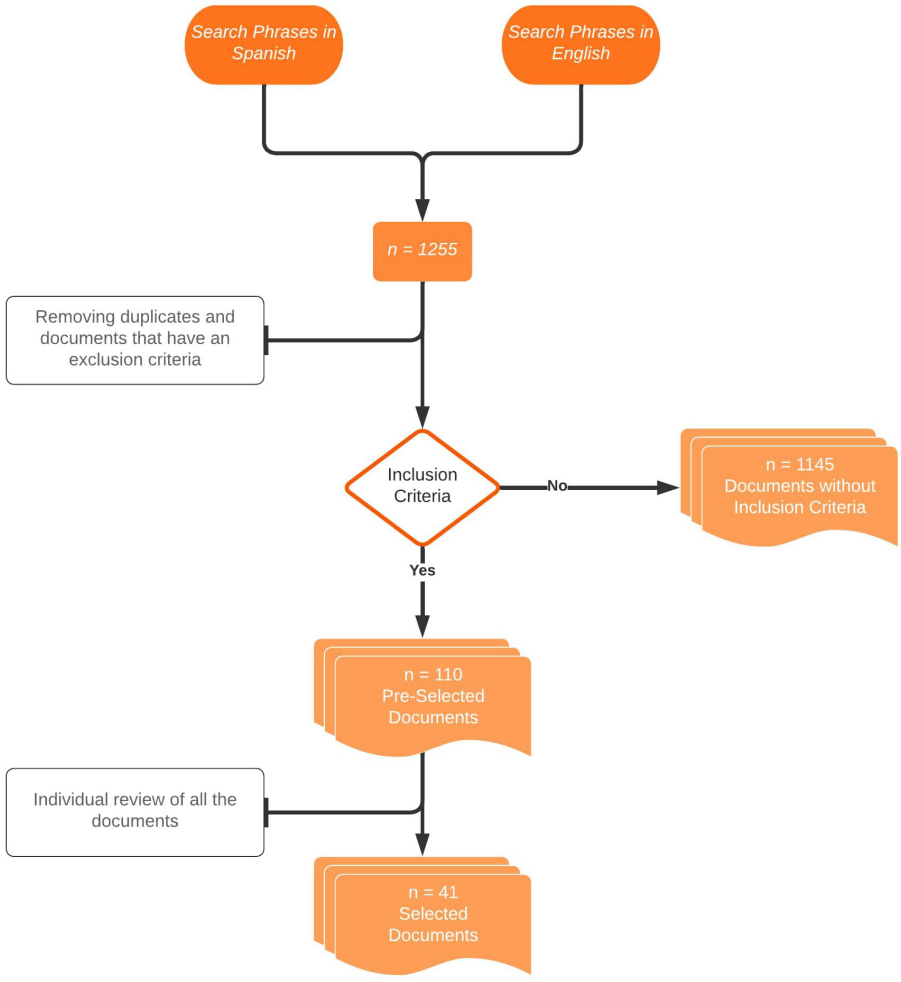


FIGURE 1
Flowchart of the document selection processed.

multifaceted academic study. Government sources, such as the U.S. Department of Homeland Security, and international organizations like UNHCR, provide essential official data. For understanding this situation. On the other hand, non- governmental organizations such as Amnesty International and Human Rights Watch offer critical perspectives rooted in human rights, based on independent research. Prestigious media outlets, like the BBC, AP NEWS, and The Guardian, provide up-to-date information, though it is important to consider potential editorial biases in some of these types of sources. Think tanks, such as CSIS, deliver in-depth analyses of the implications of migration technologies, which should be complemented by other viewpoints. Finally, specialized blogs, while less formal, can capture emerging voices but require critical evaluation of their quality. Quantitatively, media outlets constitute 33.3% of the total sources, followed by government sources (26.7%), NGOs (16.7%), think tanks (13.3%), and blogs (10%). This distribution reflects a multidimensional approach, with a strong emphasis on journalistic and governmental sources, complemented by critical analyses from NGOs and think tanks.

### 2.3 Data extraction and synthesis

The data extraction and synthesis process was carried out meticulously, focusing on four key areas that align with the objectives of this research: (a) types of technologies used, (b) countries of implementation, (c) types of organizations employing them, and (d) adopted migration strategies. The synthesis of the main findings from each document is included in a summary Table 1, which provides a clear overview of the relevant insights gathered from the selected sources.

## 3 Analysis procedure

To identify trends, categories and broader themes of analysis, a process for conducting thematic analysis of the literature was carried out (Lochmiller, 2021).

### 3.1 Reading and familiarization with the data

Initially, the three researchers thoroughly read the 41 selected documents with the aim of understanding the overall content and the topics covered. During this preliminary reading, detailed notes were taken, highlighting key ideas and themes that appeared recurrently in the texts.

### 3.2 Coding of relevant information

At this stage, significant words, phrases, and ideas that were important or frequently mentioned in the documents were identified. These units of meaning were highlighted and assigned labels or "codes" that summarized their essential content. This process allowed for systematic organization of the information and facilitated the identification of central concepts.

### 3.3 Grouping of codes into categories

Subsequently, the codes were analyzed to find similarities and relationships between them. Codes that were related or similar were grouped into broader categories that represented general concepts. For example, codes such as "drones" and "surveillance cameras" were integrated under the category of Surveillance Technologies. Likewise, to create larger thematic groupings, frequency observations were made, indicating relevant themes.

## 4 Results

Following the extraction and synthesis procedure, the information was analyzed based on the identification of patterns and trends.

### 4.1 Emerging categories

The emerging categories identified were the following:

- Technological Devices for Detection and Identification of Migrants
- Technological Devices for Obstruction of Migrants
- Artificial Intelligence
- Mobile Applications for Surveillance and Management of Migrants
- Mobile Applications for Social Inclusion of Migrants.

### 4.2 Identified patterns

#### 4.2.1 Themes

Concerning the data analysis, a detailed evaluation of various technologies used for migration surveillance and management was conducted. The following themes emerged:

1. Technologies and Strategies for Control, Management, and Surveillance by Governments.
2. Technologies for Social Inclusion by Non-Governmental Organizations.

1. Description Theme 1: Technologies and Strategies for Control, Management, and Surveillance by Governments.

- Technologies and Strategies for Control, Management, and Surveillance by Governments: Currently, nations are investing in digital borders capable of detecting people, vehicles, and animals along their boundaries, as well as employing devices for facial recognition and location tracking of migrants (Mijente, 2021). Specifically, the United States has implemented a sophisticated technological infrastructure to control immigration at its borders. This infrastructure

TABLE 1 Selected documents.

| No. | Link | Publication Date | Title | Source | Type of Document | Findings |
|---|---|---|---|---|---|---|
| 1. | https://www.swissinfo.ch/spa/migrantes-y-tecnolog%C3%ADa-c%C3%B3mo-los-m%C3%B3viles-cambian-la-ruta-~hacia-estados-unidos/48299154 | February 19, 2023 | Migrants and technology: how mobile phones are changing the path to the United States | Swiss Info | News | • Technology: CBP<br>• Type of use: Governmental<br>• Country of use: USA<br>• Implemented for: accelerating asylum application processes. |
| 2 | https://www.bbc.com/mundo/noticias-47198526 | February, 12, 2019 | Trump and the wall: what the technology looks like at the border fence between Mexico and the United States | BCC NEWS | News | • Technology: Integrated Fixed Towers (IFT), longer range cameras and radars, Sensors, mobile surveillance trucks, night vision goggles<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: detect, identify, and locate those who try to cross illegally. |
| 3 | https://idehpucp.pucp.edu.pe/boletin-eventos/muros-digitales-las-implicaciones-de-las-nuevas-tecnologias-digitales-en-~fronteras-28252/ | May 30, 2023 | "Digital walls" the implications of new digital technologies on borders | The Institute of Democracy and Human Rights (Idehpucp) is an academic unit of the Pontifical Catholic University of Peru | Bulletin | • Technology: ground sensors, identification systems, video drones, facial recognition, artificial intelligence, surveillance towers, biometric technology, CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: identify and locate suspicious activities on the ground, border guarding through continuous aerial surveillance, streamline detention and deportation processes, decision-making in the visa process, and improve the border security, prevention, and surveillance at the border. The use of the towers is correlated with an increase in migrant deaths, analyze and process physiological characteristics such as footprints, irises, and facial features, use geolocation and facial recognition data to recognize, track, and save applicant data from their arrival at the border. According to the U.S. government, it is implemented to improve the efficiency of the CBP system. |
| 4 | https://www.latimes.com/espanol/eeuu/articulo/2024-03-14/eeuu-requiere-que-migrantes-sin-pasaporte-se-sometan-a-reconocimiento-facial-para-abordar-vuelos | 14, 2024 | U.S. requires migrants without passports to undergo facial recognition to board flights | Los Angeles Times | News | • Technology: facial recognition<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: identity verification for Department of Security files. |
| 5 | https://www.acnur.org/noticias/historias/chile-migrapp-la-joya-del-sjm-que-conecta-tecnologia-y-solidaridad-celebra-dos | Aug 13–21 | Chile: Migrapp, the jewel of the SJM that connects technology and solidarity, celebrates 2 years of operation | UNHCR | | • Technology: Migrapp<br>• Type of use: Non-governmental (Jesuit migrant service SJM and funded by UNHCR)<br>• Country of use: Chile<br>• Implemented to: promote social inclusion and access to rights of refugees and migrants in Chile. It has managed to amplify the delivery of guidance at different moments of the migrant process and in the delivery of a response that understands refugees and migrants as subjects of rights and with active listening beyond virtuality. |

*(Continued)*

TABLE 1 (Continued)

| No. | Link | Publication Date | Title | Source | Type of Document | Findings |
|---|---|---|---|---|---|---|
| 6 | https://www.elsaltodiario.com/migracion/tecnologias-se-usan-para-vigilar-personas-migrantes-despues-se-usan-resto-poblacion | 10-Jun-22 | Cinthya Rodriguez: "The technologies that are used to monitor migrants are then used with the rest of the population" | The Daily Leap | News | • Technology: electronic shackles, smart link app, drones, security cameras and motion sensors<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: locate people in real-time, record voice, and communicate, the Smart Link app allows ICE officers to permanently follow the steps of migrants, who must report frequently (weekly, daily, even several times a day) and send selfies, Monitor, and control everything that happens at the border, contain the entry of undocumented immigrants. The sensors identify movement and have been placed to cover the stretch of the border. |
| 7 | https://www.eltiempo.com/mundo/eeuu-y-canada/esta-es-la-tecnologia-que-usa-cbp-para-detectar-a-los-indocumentados-en-una-zona-3326426 | 20.03.2024 | This is the technology CBP uses to | Weather | News | • Technology: security cameras, motion sensors<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: monitoring, and sending agents if necessary, to the most inhospitable corners |
| 8 | https://www.telemundo.com/noticias/noticias-telemundo/hispanos-en-ee-uu/muro-fronterizo-tecnologia-inteligencia-artificial-rcna129274 | December 12, 2023 | Technology for a digital wall: how artificial intelligence and video surveillance are used on the border | Telemundo | News | • Technology: surveillance towers, Artificial Intelligence for vehicle scanning, robot dogs, license plate readers, facial recognition<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: scanning several kilometers at a distance and scanning private and cargo vehicles when crossing the border (the creation of this technology was requested), Patrol the border, Video surveillance. |
| 9 | https://www.youtube.com/watch?v$=$cATMumgHwoI | March 30, 2024 | Technology for a digital wall: how artificial intelligence and video surveillance are used on the border | Milenial Digital | News | • Technology: electronic shackles Type of use: Government<br>• Country of use: USA<br>• Implemented to: monitor migrants who are within their territory waiting for a court date while they regulate their immigration status |
| 10 | https://www.state.gov/translations/spanish/hoja-informativa-el-gobierno-de-ee-uu-anuncia-nuevas-medidas-energicas-para-gestionar-la-migracion-regional/ | April 27, 2023 | Fact Sheet: U.S. Government Announces New Crackdown to Manage Regional Migration | The U.S. Government | Fact Sheet | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: request asylum appointments |
| 11 | https://www.es.amnesty.org/en-que-estamos/reportajes/derechos-personas-refugiadas-y-migrantes-en-la-era-digital/ | March 15, 2024 | Migrants' rights in the digital age | Amnesty International | Report | • Technology: CBP one, electronic tracking devices, facial and voice recognition applications, radars, high-tech cameras and drones, artificial intelligence powered surveillance towers, biometrics<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: schedule an appointment and present yourself at a port of entry, instead of attempting to enter areas located between such ports, controlling migrants and asylum seekers outside the prison |

*(Continued)*

TABLE 1 (Continued)

| No. | Link | Publication Date | Title | Source | Type of Document | Findings |
|---|---|---|---|---|---|---|
| | | | | | | environment. Examples include the Intensive Supervision Appearance Program (ISAP) and the Border Monitoring, Surveillance, and Monitoring Devices Program, Identification, Verification, and Authentication of Persons at the Border |
| 12 | https://www.state.gov/translations/spanish/ficha-informativa-cbp-one-facilito-mas-de-170-000-citas-en-seis-meses-y-continua-siendo-una-herramienta-segura-ordenada-y-humana-para-la-~gestion-de-fronteras/ | August 3, 2023 | Factsheet: CBP One facilitated more than 170,000 appointments in 6 months and continues to be a safe, orderly, and humane tool for border management | U.S. Department of State | Press Release | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: scheduling an appointment and presenting yourself at a port of entry, rather than attempting to enter areas located between those ports |
| 13 | https://www.france24.com/es/am%C3%A9rica-latina/20230329-un-mejor-tel%C3%A9fono-para-sortear-los-fallos-de-la-app-cbp-one-as%C3%AD-es-la-lucha-por-lograr-asilo-en-ee-uu | 29/3/2023 | A better phone to get around the failures of the CBP One app, this is the fight to achieve asylum in the US | France 24 | News | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: scheduling an appointment and presenting yourself at a port of entry, rather than attempting to enter areas located between those ports |
| 14 | https://www.hrw.org/es/news/2024/05/01/ee-uu-el-mecanismo-de-entrada-digital-cbp-one-expone-migrantes-danos | May 1, 2024 | U.S.: "CBP One" Digital Entry Mechanism Exposes Migrants to Harm | Human Rights Watch | New | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: schedule an appointment and report to a port of entry, rather than attempting to enter areas located between those ports |
| 15 | https://www.interior.gob.cl/noticias/2021/09/30/gobierno-anuncia-medidas-para-enfrentar-la-migracion-en-la-zona-norte/ | September 30, 2021 | Government announces measures to tackle migration in the northern zone | Ministry of the Interior and Public Security, Government of Chile | Press Release | • Technology: trucks with satellite antennas<br>• Type of use: Government<br>• Country of use: Chile<br>• Implemented for: monitoring to reinforce the surveillance of migrants in the northern part of the country. |
| 16 | https://www.vozdeamerica.com/a/dificultades-enfrentan-migrantes-cbp-one-/6924643.html | January 19, 2023 | What difficulties do migrants face with the CBP One app? | Voice of America | News | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: schedule an appointment and present yourself at a port of entry, instead of attempting to enter areas located between those ports |
| 17 | https://cnnespanol.cnn.com/video/ice-telefonos-rastreo-migrantes-perspectivas-buenos-aires/ | June 6, 2022 | ICE uses cellphones without internet to track migrants | CNN en Spanish | News | • Technology: Smartlink App<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: tracks via phones |
| 18 | https://www.lanacion.com.ar/el-mundo/tension-en-la-frontera-entre-mexico-y-eeuu-sensores-de-calor-drones-black-hawk-y-hasta-perros-robot-nid11052023/ | May 12, 2023 | Tension on the border between Mexico and the U.S.: heat sensors, drones, Black Hawk and even "robot dogs" to stop the crossing of migrants | La Nación | News | • Technology: robot dogs, drones and heat sensors<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: tracking and monitoring migrants |

*(Continued)*

TABLE 1 (Continued)

| No. | Link | Publication Date | Title | Source | Type of Document | Findings |
|---|---|---|---|---|---|---|
| 19 | https://www.elheraldo.hn/elheraldoplus/investigaciones/hondurenos-migracion-estados-unidos-monitoreo-grilletes-gps-KB13745168 | June 3, 2023 | Honduran migrants, among the most monitored by the United States | The Herald | News | • Technology: electronic shackles<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: prevent migrants from waiting in prison for a judicial resolution of their immigration status |
| 20 | https://hias.org/es/noticias/app-CBP-one-grandes-desafios/ | November 8, 2023 | For Asylum Seekers, the CBP One App Poses Major Challenges | Hebrew Society for Immigrant Aid (HIAS) | News | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: Request an appointment |
| 21 | https://www.bbc.com/mundo/noticias-internacional-65539740 | May 11, 2023 | End of Title 42: the new measures that tighten control over migrants arriving at the U.S. border | BBC News | News | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: request an appointment |
| 22 | https://www.tni.org/es/art%C3%ADculo/la-frontera-omnipresente | November 24, 2023 | The omnipresent border, the digital infrastructure of migration control in the Americas | Transnational Institute | Specialized Blog | • Technology: robot dogs, biometric collection devices<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: Border surveillance |
| 23 | https://calmatters.org/calmatters-en-espanol/2024/01/la-patrulla-fronteriza-instalara-casi-300-torres-de-vigilancia-adicionales-en-la-frontera-entre-~mexico-y-california/ | January 30, 2024 | Border patrol to install nearly 300 additional watchtowers on Mexico-California border | Call matters | News | • Technology: watchtowers, artificial intelligence<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: autonomously identify and track "objects of interest", such as humans or vehicles |
| 24 | https://buslahr.medium.com/the-use-of-technology-at-an-increasingly-busy-u-s-mexico-border-66c41cd01a2c | April 12, 2024 | The Use of Technology at an Increasingly Busy U.S.-Mexico Border | Medium | News | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: scheduling an appointment and presenting yourself at a port of entry, rather than attempting to enter areas located between those ports |
| 25 | https://www.dhs.gov/sites/default/files/publications/2011005-hoja-informativa-immigracion.pdf | May 22, 2022 | Sensible and effective border security and immigration control | U.S. Department of Homeland Security | Press Release | • Technology: inspection systems, mobile surveillance systems, video systems for remote surveillance, thermal detection systems, radiation detection portals, and driver's license readers<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: border surveillance and illegal entry of migrants |
| 26 | https://features.csis.org/Tracked-Migration-Technology-and-Human-Rights/ | December 15, 2022 | Tracked: stories at the intersection of migration, technology, and human rights | Center for Strategic & International Studies | Specialized Blog | • Technology: drones, night vision goggles, biometric systems<br>• Type of Use: Government<br>• Country of Use: USA, Mexico<br>• Implemented for: managing who arrives or passes through your countries |
| 27 | https://www.amnesty.org/en/latest/news/2024/02/global-amnesty-international-publishes-an-introduction-to-defending-the-rights-of-refugees-and-migrants-in-the-digital-age/ | February 5, 2024 | Global: Amnesty International publishes an introduction to defending the rights of refugees and migrants in the digital age | Amnesty International | News | • Technology: Intensive Appearance Monitoring Program and Electronic Device Surveillance Program<br>• Type of use: Government Country of use: USA<br>• Implemented for: monitoring migrants and asylum seekers released from detention |

*(Continued)*

TABLE 1 (Continued)

| No. | Link | Publication Date | Title | Source | Type of Document | Findings |
|---|---|---|---|---|---|---|
| 28 | https://cl.usembassy.gov/fact-sheet-third-ministerial-meeting-on-the-los-angeles-declaration-on-migration-and-protection-in-guatemala/ | May 7, 2024 | Fact Sheet: Third Ministerial Meeting on the Los Angeles declaration on migration and protection in guatemala | U.S. Embassy in Chile | Press Release | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: request an appointment |
| 29 | https://www.migrationpolicy.org/sites/default/files/publications/mpi-contemporary-border-policy-2024_final.pdf | January 2024 | Shifting Realities at the U.S.-Mexico Border | U.S. Immigration Policy Program | Technical Report | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: request Asylum Appointments |
| 30 | https://www.jrsusa.org/wp-content/uploads/sites/2/2024/04/Final_JRS_2024_Policy-Brief_Navigating-U.S.-Mexico-Border-JU2.pdf | April 17, 2024 | Navigating the U.S. - Mexico Border - Digital Practices of Migrants and Their Psychosocial Needs | Jesuit Refugee Service-USA | Technical Report | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: request an appointment |
| 31 | https://www.amnestyusa.org/reports/the-digital-border-migration-technology-and-inequality/ | May 21, 2024 | The digital border: migration, technology and inequality | Amnesty International | Technical Report | • Technology: Military-grade surveillance and deterrence technologies, including a network of security towers equipped with cameras, heat sensors, motion sensors, and other so-called "smart" border technologies, Advanced Homeland Reconnaissance Technology System (HART).<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: border surveillance and illegal entry of migrants |
| 32 | https://www.amnesty.org/en/latest/news/2024/05/global-new-technology-and-ai-used-at-borders-increases-inequalities-and-undermines-human-rights-of-migrants/ | May 21, 2024 | Global: New technology and AI used at borders increases inequalities and undermines human rights of migrants | Amnesty International | News extracted from the technical report "The digital frontier: migration, technology and inequality" | • Technology: biometric sensors, drone surveillance, CPB One<br>• Type of use: Government Country of use: USA<br>• Implemented for: border surveillance and illegal entry of migrants |
| 33 | https://www.csis.org/analysis/expanding-use-technology-manage-migration | March 6, 2023 | The expanding use of technology to manage migration | CSIS Center for strategic international studies | Technical Report | • Technology: drones, cell phone data, geolocation data, digital travel documents, aerial imagery<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: migrant location |
| 34 | https://www.ohchr.org/en/video/2023/digital-technologies-and-migration | Sep 18, 2023 | Digital technologies and migration | United Nations | News | • Technology: biometric data, automated visa applications, emotion detection system, drones<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: location of migrants |
| 35 | https://apnews.com/article/technology-united-states-government-caribbean-mexico-mobile-apps-49b38b18869ed3b2260fb6d774153456 | January 28, 2023 | Online system to seek asylum in US is quickly overwhelmed | Apnews | News | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: request Asylum Appointments |

*(Continued)*

TABLE 1 (Continued)

| No. | Link | Publication Date | Title | Source | Type of Document | Findings |
|---|---|---|---|---|---|---|
| 36 | https://www.wired.com/story/help-migrants-border-aid-groups-deploy-tech/ | Aug 11, 2019 | To help migrants at the border, aid groups deploy tech | Wired | News | • Technology: digital locker, storage tool from Innovation Law Lab, Mobile technology with a WhatsApp and Facebook messaging program<br>• Type of use: Non-governmental<br>• Country of use: USA<br>• Implemented for: helping immigrants and human rights defenders, Offers health advice (how to avoid dehydration or cholera, for example) and maps that guide migrants to shelters used by The International Committee on Human Rights (ICRC). Red Cross (ICRC) |
| 37 | https://www.latimes.com/business/story/2023-05-17/how-tiktok-and-other-social-media-changed-the-way-people-migrate-to-the-u-s-in-the-title-42-era | May 17, 2023 | "Their only lifeline" for migrants at the U.S. border: smartphones and TikTok | Los Angeles Time | Blog | • Technology: use of TikTok, Facebook, YouTube, and other social media sites, CBP One<br>• Type of use: Non-Government<br>• Country of use: USA<br>• Implemented to: share updates about the policy change and how it might affect them; Make an appointment and report to a port of entry, rather than attempting to enter areas between those ports |
| 38 | https://www.cbp.gov/newsroom/national-media-release/cbp-releases-january-2024-monthly-update | 02/13/2024 | CBP Releases January 2024 Monthly Update | US Customs and border protection | Press release | • Technology: CBP One; The Global Entry mobile app and mobile passport control, as well as the new Global Entry contactless portals<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: scheduling an appointment and reporting to a port of entry, rather than attempting to enter areas located between those ports; Protect passenger privacy and streamline arrival processing by eliminating paper receipts |
| 39 | https://bipartisanpolicy.org/download/?file$=$/wp-content/uploads/2021/05/Immigration-Border-SecurityV3.pdf | May-21 | Redefining border security | Bipartisan Policy Center's | Technical Report | • Technology: tunnel detection as a border<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented for: cybersecurity protection, tunnel detection technology. as a border increase in fences and infrastructures, use of tunnels |
| 40 | https://www.theguardian.com/us-news/2024/feb/06/us-immigration-bill-mexico-border-surveillance-privacy | Tue 6 Feb 2024 | A privacy nightmare': the $400 m surveillance package inside the US immigration bill | The Guardian | News | • Technology: sensors, on-board computing and artificial intelligence, mobile video surveillance systems and drones, automated surveillance towers, autonomous towers Anduril<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: protect the privacy of the people to identify items of interest and control migration |
| 41 | https://www.hrw.org/news/2024/05/01/us-digital-metering-system-exposes-migrants-harm | May 1, 2024 | US: digital metering system exposes migrants to harm | Human Rights Watch | Press release based on a report | • Technology: CBP One<br>• Type of use: Government<br>• Country of use: USA<br>• Implemented to: schedule an appointment and report to a port of entry, rather than attempting to enter areas located between those ports, to limit the number of asylum seekers processed at ports of entry each day, and to return others to Mexico. |

includes high-tech surveillance systems such as fixed towers equipped with cameras and radar, motion sensors, mobile surveillance trucks, and drones. In addition, the U.S. utilizes biometric technologies and communication interception tools to identify, track, and monitor migrants. In Mexico, some of these technologies have also been adopted, though their implementation is less extensive compared to the United States. In Chile, satellite antenna-equipped trucks are used for monitoring and surveillance of migrants in the northern region of the country.

- Technological Devices for Obstructing People: In the United States, the Digital Border Wall represents a technological barrier integrating multiple devices to prevent the passage of individuals, while considering that data tracking poses a risk for asylum seekers, as this information could be used against them due to a lack of transparency in the registration and storage of private data (Witteborn, 2022). This system combines cameras, sensors, and other advanced technologies to create a robust defense, evolving traditional border control strategies into a more effective and technological integration.
- Artificial Intelligence: The use of AI at borders presents many ethical and moral challenges, as it can reinforce stereotypes and oversimplify the complex causes of discrimination, perpetuating social inequalities (Jiménez Quiñones, 2023). The United States also employs a variety of independent technologies for immigration management. Artificial intelligence plays a crucial role in analyzing large datasets, which allows for the identification of migration patterns, assessment of potential risks, and improved efficiency in border surveillance. This data analysis, combined with other surveillance technologies, provides authorities with an unprecedented ability to track and monitor migration flows.
- Mobile Applications for Surveillance and Management: In the United States, mobile applications play a crucial role in migration surveillance and management. The CBP ONE app is used to schedule appointments and present migrants at ports of entry, as well as for facial recognition and geolocation. The Smart Link app allows ICE officers to continuously monitor the movements of migrants, who must frequently check in and send selfies to confirm their location. These government-implemented applications for migration management have become facilitators of social classification, assessing risks associated with migrant entry (Leese et al., 2022). Additionally, automated visa applications streamline visa processes through automated technologies.

2. Description Theme 2: Technologies for Social Inclusion by Non-governmental Organizations.

According to the review data the only technology designed for social inclusion is the chilean Migrapp app, developed by the Jesuit Migrant Service and funded by UNHCR, facilitates social inclusion and access to rights for migrants and refugees. It provides guidance and essential resources, supporting migrants in their integration into society. This app, developed by the Jesuit Migrant Service and funded by UNHCR, serves as a tool for promoting social inclusion and that migrants and refugees have access to essential rights and services. It provides information on documentation, legal processes, public services, and community resources, helping migrants navigate local systems and overcome potential barriers to integration. It also offers guidance on cultural adaptation and employment searches, along with real-time support from advisors and migration experts. Through its community-building features, such as forums and discussion groups, Migrapp helps migrants establish support networks, enhancing both their social and emotional integration. Migrapp's comprehensive approach supports migrants throughout the entire migration process, from pre-move preparations, where it offers information on visa requirements and necessary documentation, to post-arrival integration, where it facilitates access to healthcare, education, and other essential services. Additionally, the app provides ongoing assistance for navigating cultural and labor market challenges, while helping users maintain their legal status (Servicio Jesuita a Migrantes, 2024).

## 4.3 Identified patterns

The results identified the following patterns in the use of technology for migration governance across the countries studied, which communicated that the results in this paper are aligned to previous generated data.

- Extensive Use of Advanced Technologies in the United States: The deployment of fixed towers, drones, cameras, and sensors demonstrates a comprehensive and sophisticated approach to migration surveillance and control in the U.S. This reflects the country's strong investment in emerging technologies for border management (Mijente, 2021; Jiménez Quiñones, 2023; Witteborn, 2022).
- Limited Use of Technologies in Mexico and Chile: While both countries utilize emerging technologies, their implementation is considerably less extensive than in the United States. The technological tools used in migration governance are not as widespread or integrated into broader systems of surveillance and control (Center for Strategic International Studies, 2024; Mixed Migration Centre, 2024).
- Minimal Use of Technologies in Honduras: Unlike the U.S., Mexico, and Chile, Honduras presents a different landscape in terms of migration technology. Despite facing similar migration challenges to countries like Mexico, there is little evidence of significant use of emerging technologies for migrant detection, integration, identification, or management (International Organization for Migration, 2021; Amnesty International, 2024).
- Mobile Applications for Social Inclusion: There was only one case of a mobile application Migrapp, developed in Chile specifically for the social inclusion of migrants. This application plays an essential role in supporting migrants, demonstrating the potential of technology to ethically facilitate migration and social inclusion (Servicio Jesuita Migrante, 2024).

TABLE 2 Emerging categories and broader themes.

| Initial areas | Emerging categories | Themes |
|---|---|---|
| Type of technologies Used | Technological devices with integration for detection and identification of migrants | Technologies and strategies for control, management, and surveillance by governments |
| Countries of implementation | Technological devices for obstruction of migrants | |
| Type of organization employing the technology | Artificial intelligence | Technology for social inclusion by non-governmental organizations |

## 4.4 Analysis of technology in the phases of the migration process

To further analyze the results concerning the use of technology in the stages of migration, we have decided to adopt the framework proposed by Tizón et al. (1992). This model identifies four key stages of the migration process: preparation, the migratory act, settlement, and integration. By using this framework, we were able to systematically examine the role of technology at each phase of migration.

According to the analysis of the 41 documents, technologies focused on detecting and identifying migrants are used during the preparation phase, allowing them to plan their journey. An example of this is the use of biometric devices and surveillance cameras at borders to anticipate risks and identify the safest routes.

Additionally, during this phase, automated visa management applications are highlighted, making it easier for migrants to obtain the necessary documents before starting their journey. During the migration phase, which features the largest number of identified technologies, tools such as obstruction devices, like the Digital Border Wall in the United States, combine sensors and cameras to prevent unauthorized crossings. Mobile applications like CBP One are also used to manage appointments and monitor migrants throughout their journey, while artificial intelligence assists authorities in analyzing migration flows and predicting risks.

In the settlement phase, technologies shift their focus toward facilitating the adaptation of migrants in destination countries. Applications like Migrapp in Chile provide key information about healthcare, education, and employment services, helping migrants integrate into society.

Finally, in the integration phase, Migrapp continues to support the social and cultural inclusion of migrants, offering guidance on the labor market, legal processes, and promoting the formation of community networks that facilitate their complete integration into the host society.

## 4.5 Analysis of technologies in migration governance

The analysis of the 41 documents in Table 2 reveals that most technologies in the migration domain are geared toward the control, surveillance, and management of migrants, particularly during the migration phase. Technologies like detection and identification devices, the Digital Border Wall in the United States, and mobile applications like CBP One and SmartLink play a crucial role in monitoring and regulating migration flows.

These tools, along with the use of artificial intelligence, enable authorities to anticipate risks, track migrants, and manage their entry. However, in the preparation phase, technologies that facilitate visa management also stand out, streamlining the process of obtaining documents before migrants embark on their journey. Although the primary focus of these technologies is control, some, such as visa management applications and tools that facilitate the regularization of immigration status, indirectly contribute to the integration of migrants by reducing bureaucratic barriers. Additionally, technologies designed for social inclusion, such as the Migrapp application in Chile, provide access to essential services like healthcare, education, and employment, supporting migrants in adapting to the host society. This shows that, despite the predominance of control, certain technological elements can facilitate the integration and settlement of migrants in their new environments.

Similarly, some technologies designed for control, such as automated visa processes, although primarily intended for managing migration flows, can speed up the documentation needed for labor insertion or enrollment in social services, which are key elements of integration. In these cases, while the technology was not specifically created with a social inclusion focus, its implementation can have positive effects on integration by reducing the bureaucratic barriers migrants face when settling and fully participating in the host society. Therefore, even though the main focus of many technologies is control, certain elements in their design can facilitate key aspects of integration, such as the legalization of immigration status, which in turn opens doors to other essential services.

## 4.6 Analysis of the potential and risks of technologies

Migration management stands at a crossroads where emerging technologies offer both potential benefits and significant risks. On one hand, the use of technology-integrated devices for the detection and identification of migrants promises greater efficiency in border management. These technologies allow for the monitoring of vast areas, identification of potential illegal crossings, and expedited processing of individuals. Similarly, the creation of "smart borders" offers increased control over migration flows through strategic obstruction. Furthermore, surveillance technologies can be valuable tools in combating transnational crimes, such as human trafficking, drug smuggling, and arms trafficking, by providing real-time information on suspicious activities (Feldstein, 2024).

However, this technological approach to migration is not without its risks. The mass collection and storage of biometric data,

geolocation information, and the use of social media surveillance could pose a serious threat to privacy and human rights (Klauser, 2018). The use of algorithms and artificial intelligence in migration governance raises concerns about perpetuating existing biases and leading to discrimination based on origin, race, or religion. Concerns may also arise regarding the ethical dilemmas posed by the implementation of AI, particularly concerning marginalized populations (Cabrera et al., 2023; Dauvergne, 2020).

Another risk associated with the use of technologies in migration processes is the lack of transparency and accountability. The opacity surrounding the use of these technologies and the lack of access to information about how data is collected, stored, and used opens the door to potential abuse. Finally, intrusive surveillance can create a climate of fear and intimidation, deterring not only migrants but also civilians from accessing essential services and exercising their fundamental rights (Molnár, 2023; ReliefWeb, 2023; International Organization for Migration, 2023).

The results of the study on the use (or lack of use) of technology in migration across the United States, Mexico, Honduras, and Chile largely align with the theoretical framework and methodological expectations outlined in the introduction and methodology sections. Specifically, the extensive use of emerging technologies in the United States—such as fixed towers, drones, cameras, and sensors—reflects the country's well-established technological landscape for migration control, as anticipated. This confirms the findings of previous literature, which emphasizes the U.S.'s leadership in employing high-tech systems for surveillance and enforcement. In contrast, Mexico and Chile show more limited technological implementations, which is consistent with expectations drawn from the literature. While both countries have adopted some advanced tools, their scope and integration into migration governance are far less extensive compared to the U.S. This finding matches the research premise that countries with less developed infrastructure face challenges in deploying technology at a comparable scale. Honduras, as predicted, represents an even more technologically underdeveloped context, lacking significant resources for managing migration through advanced technology. This reinforces the conclusion that countries with limited technological capacity face greater challenges in migration governance, as outlined in the methodology.

## 5 Discussion and conclusions

According to the findings of this research, there is evidence that technology applied in migration processes in the Americas has primarily focused on surveillance and control, functioning as a tool of power and discipline, affecting both migrants and host societies. This approach is more evident in countries like the United States, where technological development is more advanced. The data also show significant ambivalence: it can facilitate both exclusion and social integration. For instance, in the U.S., advanced technological tools—including mobile apps, facial recognition systems, emotion detection, and drones— not only expedite migration governance but also intensify control over migrants. These practices reflect Michel Foucault's concept of "biopower," which describes how control shifts from mere territorial management to the governance of populations, disciplining and shaping behaviors to subjugate those on the margins of society (Foucault, 1975).

In Mexico, despite efforts to implement similar technologies, insufficient technological landscape limits their effectiveness compared to the United States. This situation is similar in Chile, where technological disadvantages are also faced. However, an exception is the "Migrapp" application, which promotes social integration with the support of non-governmental organizations, in a context generally dominated by the use of technology for exclusion, generated and enhanced by civil society and international organizations. On the other hand, Honduras is in an even more unfavorable situation due to the general lack of human and technological resources, further exacerbating the vulnerability of its migrant population in the face of digitized migration processes in northern countries.

It is at this point that it becomes crucial to reflect on the concept of "social technologies," introduced in this article, as those designed to promote inclusion and social wellbeing. However, the technologies analyzed in this study diverge from this ideal, perpetuating dynamics of exclusion and control instead. This paradox not only affects migrants but also governmental institutions and their public policies, transforming migration control into a "total social fact" that, as Ramonet (2020) describes, destabilizes not only social and political expectations but also conceptions about vulnerable populations. In this framework, migrants are simultaneously perceived as a threat and as a group in need of differentiated help, reinforcing technology as a tool of power (Méndez-Fierros, 2023).

To better understand these dynamics, it is useful to turn to thinkers like Mbembe (2003), who analyzes how power subjects entire populations to what he calls a "zone of non-being", and Butler (2020), who highlights how these practices reinforce the exclusion and dehumanization of migrants. Additionally, Deleuze (1992) suggests that these technologies represent a new phase in the evolution of control societies, where power infiltrates all spheres of social life.

The growing dependence on surveillance and control technologies in migration governance poses significant risks not only to human rights but also to the social structure of the societies involved. The lack of transparency and adequate regulation allows these technologies to perpetuate biases, discriminate, and reinforce existing hierarchies, transforming migrants into subjects of control that transcends the legal and punitive, penetrating the social and personal spheres of individuals.

However, the solution does not lie in eliminating technology but in ensuring that its development and use in the migration field are responsible and aligned with human rights principles. To achieve this, governments and society as a whole must adopt a forward-looking perspective, anticipating the challenges and opportunities presented by increasing digitalization.

Governments like that of the United States, with advanced technological capabilities, have the opportunity to lead with transparency and fairness, implementing these tools in a just and ethical manner. Mexico and Chile, for their part, must strengthen their technological landscape and regulatory frameworks to manage migration efficiently and with respect for rights, avoiding the creation of digital divides that exacerbate vulnerabilities. Honduras, in turn, must prioritize the development of its technological capacities to manage migration from a proactive rather than reactive stance.

The call is for global technological governance where innovation does not become an instrument of exclusion, but instead becomes technology for social wellbeing. Only through a shared vision and joint action can we build futures where technology, instead of deepening inequalities, becomes a bridge toward safer, more orderly, and dignified migration.

## Author contributions

JC-M: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. IM: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Supervision, Validation. AD: Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Investigation, Methodology, Validation. IC: Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Investigation, Validation.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Challenges of agricultural digitalization in the Guatemalan western highlands

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## 1 Introduction

Guatemala is a country located in the Central American isthmus, within a region known as the Northern Triangle. This region, consisting of Guatemala, El Salvador, and Honduras, has historically been characterized by agricultural export production, challenging political processes—including internal and cross-border conflicts—vulnerability to climate change and natural disasters (WorldRiskReport2022, 2023), and the displacement of rural populations seeking improved work opportunities and living conditions. Migration from Guatemala primarily flows to the United States, contributing ~20% of Guatemala's Gross Domestic Product (GDP), according to the Ministry of Finance (Ministry of Finance of Guatemala, 2024).

The agricultural productivity challenges faced by Guatemala are part of a global issue. Worldwide, rural communities often struggle to integrate into the global economy due to insufficient technological infrastructure, limited access to capital, and the erosion of traditional farming practices. The ongoing digital transformation in agriculture presents great potential but also highlights significant disparities between regions with robust infrastructure and areas like Guatemala's western highlands, where digital solutions remain largely inaccessible. In this context, the conversation shifts from mere technological innovation to the adaptation of tools that align with the specific social and cultural realities of these agricultural communities (Rogers, 2003).

One of the primary drivers of migration is the low productivity of small-scale farmers compared to large-scale producers. Contributing factors include land fragmentation through inheritance, traditional agricultural methods that do not always align with land suitability, and resistance to adopting new practices. Additionally, current marketing systems offer small-scale producers limited access to higher-paying markets and credit, placing them at a disadvantage. As a result, they often become reliant on a distribution system controlled by intermediaries who dominate both the supply chain and its financing.

This situation creates conditions of food insecurity, leading to both chronic and acute malnutrition, as observed by the author during her research and work in these rural areas. Compounding this issue, a significant portion of the population is of Mayan origin and faces limited access to education and credit, with added barriers due to social, cultural, and language differences.

While migration and economic challenges persist, there is a growing recognition of the potential role of digital technologies in transforming Guatemala's agricultural sector. In the context of a global shift toward digital economies, adopting digital agriculture could help address some of the root causes of migration and poverty by modernizing farming practices, increasing market access, and providing farmers with real-time critical information.

In response to these challenges, various international cooperation agencies have initiated projects with mixed results. One such effort is a public-private

partnership between the U.S. government's Feed the Future initiative, an international program aimed at combating hunger and poverty (Feed the Future, 2024), and Popoyán, a Guatemalan agricultural company committed to the concept of impact-driven business. This partnership, supported by USAID (the U.S. Agency for International Development), seeks to foster economic growth while prioritizing community sustainability and innovation (Agropecuaria Popoyan, 2024). The initiative, launched in the western highlands of Guatemala, spans five departments: Huehuetenango, Quetzaltenango, San Marcos, Totonicapán, and Quiché.

## 2 About the change of the traditional model

The Feed the Future-Popoyán alliance, established in August 2017, launched a program called ProInnova, which stands for the Project of Innovative Solutions for Agricultural Value Chains (ProInnova Project, 2024). The project aims to address malnutrition and poverty by enhancing productivity across the agricultural sector. Key components of the initiative include CAMPO (Agricultural Innovation Centers), which offer educational spaces for farmers, demonstration plots for practicing new technologies, and access to crop varieties with higher market value. In addition, financial support lines were established to strengthen value chains and assist with home improvements, while training is provided in better food preparation practices. Agricultural technicians are also deployed to support farmers directly in the field.

The program emphasizes institutional integration, but this article will focus on the viability of establishing a digital ecosystem centered on AGRICONECTA, a mobile platform that integrates e-commerce, remote digital education, and technical support through audio and video messaging services, as well as a call center and commercial support services—all in a single platform. AGRICONECTA aims to transform both the productive and social environment, delivering real-time products and services to farmers and their families. Additionally, this model introduces a shift in the approach to cooperative intervention, as the digital ecosystem is designed to promote the program's sustainability by providing a dual marketing platform, a credit facilitation space, and a means of payment.

Preliminary feedback from farmers participating in the AGRICONECTA pilot project has shown improvements in tracking crop yields and accessing real-time market price data, enabling some to negotiate better prices. However, long-term data on productivity gains and broader socio-economic impacts are still needed to fully evaluate the platform's effectiveness. A print out of the mobile app dashboard is shown hereby in Figure 1.


FIGURE 1
Agriconecta dashboard. Screenshot recovered from the authors mobile phone (2024).

## 3 About the challenges of AGRICONECTA

The question of digital intervention in the agricultural sector centers on its short-term viability, long-term sustainability, and real impact on the community, as well as identifying entry barriers and potential solutions. Generally, shifts in adoption models align with unmet needs and the pursuit of innovative, feasible, and profitable solutions. Across sectors worldwide—commerce, industry, public administration, health, and education—there is a shift toward omnichannel models, evolving from unidirectional approaches to multidirectional systems that offer comprehensive 360-degree contact strategies. Users, whether in the private or public sectors, increasingly expect consistent, frictionless interactions with entities and services across all channels, both in person and virtually.

As Lehrer and Trenz (2022) note, the broad adoption of digital technologies and evolving user behaviors have facilitated the rise of omnichannel models, where businesses leverage integrated

processes and information systems to deliver a seamless, consistent experience across numerous digital and physical touchpoints. Although this trend is increasingly recognized in business, it has not yet been fully explored in other areas, presenting new opportunities for integrating various activities as long as the ultimate objectives are well-defined and accurately implemented.

## 4 The experience and challenges

However, convenience alone does not automatically foster a sense of belonging. Theoretically, providing farmers with services that maximize benefits—by improving access to goods and services in more convenient, timely, and cost-effective ways within an ethical framework—is a sound idea that should gain universal acceptance. From a multichannel perspective, an approach that integrates in-person services through agricultural advisors, events at CAMPO centers, and resources within allied associations and community spaces, alongside an app that provides emergency support, market prices, technical assistance, an online store, online courses, and other valuable content, includes all the elements necessary to drive positive change in the targeted communities.

However, there are barriers that still need to be addressed. During visits to the communities and field observations conducted in early 2024, it was noted that beyond the aspects of service provision, there are additional areas for improvement and opportunities to explore:

Barriers to overcome:

- Limited internet and telephone coverage in the target departments
- Low levels of digital literacy, particularly among adults in the target population
- High costs of mobile and internet services, which are often unaffordable for this population
- Cultural resistance and mistrust of new technologies, especially among older adults
- Strong preference for interpersonal, face-to-face interactions
- Language barriers in regions where Mayan languages are predominantly spoken
- Limited banking access and credit services that are challenging to qualify for
- Resistance from certain community leaders who feel their influence may be diminished
- Potential competition from established, traditional service channels
- Underdeveloped logistics networks in the target areas
- High initial investment required for technological resources with delayed returns

Despite mobile phone usage rates of 82.4% among men and 72.8% among women (National Institute of Statistics, 2023), affordability remains an issue. The average monthly income for small farmers is GTQ 2,877.00, while mobile internet packages cost GTQ 199.00 (Tigo, 2024) and Starlink residential packages begin at GTQ 375 per month (Starlink, 2024). With the basic food basket costing GTQ 3,904.98, internet expenses can represent up to 6.9% of their monthly income.

On the other hand, the opportunities offered by this type of development go beyond the supply

- Greater scope of technical content that is available 24/7
- Permanent and convenient educational offer
- Improve the offer of products and prices in two ways, lower the costs of inputs for agriculture and increase the price of fresh produce in the market
- Make market processes transparent by presenting price and quality comparisons from reliable information channels.
- Offer financing options transparently
- Provide greater security in collections and payments through electronic wallet
- Allow comparison of prices of inputs and technologies
- Greater control of tracking and tracing of product flow
- Immediate user feedback
- Improved pest control
- Promote the inclusion of displaced or poorly visible groups
- The young producer seeks novelty and productive improvement

## 5 Discussion

Introducing digital media to strengthen the agricultural value chain is challenging yet filled with potential. The main obstacles include weak phone signal coverage, the need for culturally and socially relevant digital technology, and the high costs of mobile and internet services. Immediate results may be limited, but digitalization offers a path to amplifying benefits once user adoption reaches critical levels.

Similar digital platforms have shown promising results in other regions. For instance, in Sub-Saharan Africa, mobile platforms like iCow have empowered smallholder farmers with best practices for livestock management, improving yields and food security (van der Velde et al., 2020). Key lessons from these initiatives include the importance of continuous community engagement and adapting technology to local needs.

AGRICONECTA's omnichannel approach provides long-term advantages in both sustainability and adaptability. One major hurdle for digitalization in rural agricultural areas is the socio-economic and cultural divide between technology creators and the users who most need these solutions. Digital tools are generally designed by urban professionals who, often unfamiliar with rural realities, may design with urban, literate users in mind. This gap underscores the need for localized digital education initiatives that do more than introduce technology—they must help communities understand, trust, and find value in these tools. Only when this is achieved can digitalization be embraced as an asset rather than viewed as an imposition (Foster and Heeks, 2013).

While the path to full digitalization in Guatemala's western highlands faces challenges, the potential long-term benefits are substantial. Tools like AGRICONECTA aim not only to improve efficiency but also to transform the socio-economic landscape of these communities by providing access to information, markets, and educational opportunities that were previously out of reach. Success hinges not only on implementing these tools but also on ensuring they are culturally relevant, accessible, and sustainable. As technology evolves, our approach to agricultural innovation must

also advance, rooted in community Needs, co-created solutions, and long-term engagement (van der Velde et al., 2020).

Although AGRICONECTA is a digital tool, face-to-face engagement with local opinion leaders in native languages is recommended to foster a two-way process that adapts the platform to different communities. Additionally, lobbying with telecom providers to improve coverage and offer affordable pricing will be essential to support this initiative.

## Author contributions

PL: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

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## Conflict of interest

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## Generative AI statement

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# Catalyzing sustainable development: insights from the international workshop on STI policies and innovation systems in Central America

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This article examines the landscape of Science, Technology, and Innovation policies in Central America, focusing on Nicaragua, Guatemala, Honduras, and El Salvador. These nations face significant challenges in leveraging STI for sustainable development, including financial constraints and limited resources. Additionally, Central America struggles with systemic issues such as corruption, violence, and high levels of emigration, further complicating efforts to advance STI. A workshop organized by Georgetown University's Science Technology and International Affairs program brought together scholars to discuss STI policies, resulting in key recommendations. The article highlights critical challenges, including over-reliance on state funding, stagnant researcher numbers, and the pressing need for research diversification. It emphasizes the importance of youth engagement, leadership, and resilience in shaping effective STI policies. Recommendations include investing in science education, establishing governmental scientific advisory bodies, promoting research diversity, and addressing climate change through STI strategies. The findings provide valuable

insights for scholars, policymakers, and international organizations working with less developed nations globally.

KEYWORDS

**STI policy, science-diplomacy, Central America, sustainable development, capacity building**

# Introduction

In the pursuit of fostering social and economic progress, especially in developing nations, the role of scientific and technological advancements is pivotal. Some Latin American countries, over the past few decades, have proactively devised and implemented public policies to encourage the adoption and dissemination of scientific innovations, thereby stimulating domestic technological transformations (Crespi and Dutrénit, 2014). However, the less developed countries in Central America such as Nicaragua, Guatemala, Honduras, and El Salvador, grapple with an array of challenges, encompassing financial constraints, inadequate infrastructure, a scarcity of human resources, and the absence of crucial institutions and policies (Obinna, 2019; Appolloni, 2009).

In this context, Central American countries face difficulties in effectively harnessing expertise and achievements in Science, Technology, and Innovation (STI) due to limited resources and inefficient national innovation systems, which emerges as a primary hurdle (Casalet and Buenrostro, 2014). Despite recent initiatives and dialogues with international organizations, these smaller nations have received limited academic attention, with most studies concentrating on the larger, more industrialized countries in the region.

To tackle these challenges and with the ultimate goal to pave the way for accelerated sustainable growth and improved living standards in the Central American region, the Science Technology, and International Affairs program of Georgetown University (STIA), took the initiative to organize an international workshop. The workshop served as a platform for scholars from Central America, Colombia, Venezuela, Mexico, Spain, and the US to deliberate on the current state of STI policies and scientific development in the region. By focusing on five general topics, including the status of STI policies and scientific development, the evolving role of STI policies in Latin America, empowering the next generation of scientists, building resilient innovation ecosystems for sustainable development, and perspectives from international scientific societies and funding institutions, the workshop aimed to delve into the intricacies of STI policies and scientific progress in Central America.

The findings presented in this article stem from the discussions held during the workshop. These insights aim to inform policymakers, scholars, and practitioners on the development of more robust and effective STI policies in Central America, contributing to the broader discourse on science governance and diplomacy. Furthermore, the recommendations generated offer valuable guidance for international organizations and development agencies working with less developed countries, highlighting the global relevance of the challenges and potential solutions discussed.

The following section introduces the key topics discussed during the workshop, covering the history of science and technology policies in the region, their current state, and the future perspectives identified.

# The challenge of doing science in Latin America

## Colonial foundations and post-independence legacy

Latin America was created by the colonization of large portions of the Americas by Spain and Portugal in the early 16th century, yielding one Portuguese-speaking nation (Brazil) and 16 Spanish-speaking nations scattered across Central America, South America, and the Caribbean (Crowley and Roger, 2016; Fernández-Armesto and Giraldo, 2024). The Portuguese and Spanish Empires were constructed as extractive systems designed to transfer wealth and resources from the colonies to the crown, laying the institutional foundations for the later evolution of economies based on the export of commodities rather than the autonomous production of goods and knowledge. Power was concentrated in a centralized viceregal bureaucracy whose power was guaranteed by imperial troops to ensure the continued flow of wealth to the royal houses of Europe.

The systems of extraction that emerged from this common beginning varied from place to place depending on geography, climate, the character of the indigenous population, and over time on the degree of European settlement and participation in the Atlantic Slave Trade. While these colonial powers often focused on extraction and exploitation, they also established universities and other institutions of higher learning, though access to these institutions was primarily limited to the elite. Nonetheless, in the years since achieving independence in early 19th century, it has proved difficult for Latin American nations to escape the political legacy of autocracy and the economic legacy of commodity export to produce democratic regimes capable of independently producing goods, services, and knowledge salable in the global economies that emerged first in the late 19th and early 20th centuries, and more recently in the late 20th and early 21st centuries (Weaver, 2018).

### Current challenges

A survey of indicators of economic development, internal investment, freedom, the rule of law, exposure to violence, and state fragility reveals a diversity of outcomes across the region (Massey, 2023). Over the years, some countries, such as Argentina, Chile, Uruguay, and Costa Rica, have made significant progress toward democratic governance and economic development, though they continue to grapple with the legacies of colonialism, authoritarianism, and inequality. Others remain mired in authoritarian governance and economic dependence on the export of a limited range of commodities (e.g., Cuba, Honduras, Nicaragua, and Venezuela).

Whatever their relative success within the region, compared to nations in Europe and North America, to date most Latin American countries have not been very successful in creating the institutional structure to enable meaningful contributions to the global, information-based knowledge economy of the 21st century, which requires significant public and private investment in science and technology (Petras and Veltmeyer, 2014).

### Pathways to progress

Given the historical heterogeneity of the national trajectories that emerged from common origins in Spanish and Portuguese colonialism, there can be no simple formula for development applicable uniformly throughout the region. Progress must begin with a thorough understanding of each nation's social, political, and economic history, and the configuration of formal institutions and informal practices that have resulted from that history. Moreover, addressing the issue of corruption, which has plagued many countries in the region, is essential for sustainable development (Mauro, 1995; Seligson, 2002). Building on such an understanding, policymakers can then work to develop the political strategies and organizational practices required to adapt existing social and economic structures to better foment scientific research and sustain the technological innovation needed for growth in the post-industrial economy of the 21st century.

## The resilience of Central American ethnic communities

Indigenous communities in Latin America struggle disproportionately with poverty and social exclusion (Davis, 2002). Central American ethnic communities confront unique challenges amidst the region's socio-political complexities, particularly the prevalence of violence in Honduras, El Salvador, Guatemala, and Nicaragua (Jesus and Hernandes, 2019). The Nicaraguan government's plans to build an inter-oceanic canal raise concerns about the impact on indigenous rights (Berryhill, 2015) and the environment (Huete-Pérez et al., 2016). To ensure that the benefits of development projects are equitably distributed and that they reach marginalized communities, it is crucial to adopt inclusive and participatory development processes that prioritize the voices and needs of local communities. In this context, assessing the readiness for rebuilding innovation systems becomes crucial. Indigenous environmental defenders, who often operate under challenging and underreported risks, play a significant role in these efforts. Moreover, funding dynamics must align with the goal of establishing a stable societal foundation, one that supports scientific and technological advancement while safeguarding these communities' contributions to sustainable development.

Social, environmental, and sustainability research plays a key role, revealing ecological and cultural impacts. Governments must address challenges faced by indigenous communities, necessitating nuanced governance approaches. Policies should extend beyond innovation systems, fostering an inclusive, sustainable, and culturally sensitive environment. Governance structures must engage with underreported risks, ensuring enforcement of international human rights laws. Effective policies should address environmental changes, support modern tools for communication, and tackle critical issues such as undisclosed concessions within indigenous territories, promoting transparency and accountability. This holistic approach aims to empower Central American ethnic communities in the face of multifaceted challenges.

## Navigating the challenges and opportunities of science, technology, and innovation

Central America aspires to build a robust STI ecosystem to drive sustainable development and improve the lives of its citizens. However, the region faces intricate challenges that demand nuanced policy responses and strategic interventions.

## A common thread of obstacles

Central America's Science, Technology, and Innovation (STI) landscape faces intricate challenges demanding nuanced policy responses. Current limitations, including heavy reliance on state funding for universities, hinder the implementation of effective institutional models (Padilla-Pérez and Gaudin, 2014). The prevalence of Medical Sciences underscores the necessity for diversification in research pursuits, especially given stagnant researcher numbers.

Central America is grappling with intricate challenges in the realm of Science, Technology, and Innovation (STI). From institutional dismantling in Nicaragua (Puig and Serra, 2020) to educational obstacles in El Salvador and environmental issues in Guatemala, the region faces multifaceted hurdles that demand urgent attention. These challenges encompass issues such as limited local prospects in Panama, structural educational problems hindering scientific development in El Salvador, and the need for strategic focus on high-level education in Guatemala.

Roles within National Innovation Systems spotlight the state's funding responsibility, businesses supporting industry-related research, and universities contributing to societal benefit. However, aligning STI policies with broader development goals necessitates strategic reevaluation. Central America's resource constraints call

for tailored STI resources, urging the formulation of robust policy frameworks.

The analysis illuminates multifaceted challenges, stressing the critical role of financial investment, the need for tailored policy frameworks, and the imperative of addressing systemic issues for innovation and sustainable development in Central America.

# Country-specific issues

While Central America faces common regional challenges in Science, Technology, and Innovation (STI), each country grapples with unique obstacles and opportunities that shape its individual STI landscape.

## Guatemala

Guatemala faces pressing challenges in STI, exacerbated by an economic model harming natural elements vital for health and agriculture, particularly deforestation (with 12% of tree cover loss from 2001 to 2023 driven by deforestation itself, according to data from the Landsat Program, processed by researchers at the University of Maryland) and water access (with most rural areas lacking improved sources and only 70% of the population having basic drinking water). A study by Bullock et al. (2020) found that deforestation and forest degradation are significant issues in Guatemala's protected areas. The study indicates that the combined factors (broader impact of forest disturbance, including degradation and natural disturbances) have significantly impacted the protected areas, with some experiencing disturbance rates exceeding 95%. This underscores the urgent need for environmentally focused STI initiatives to combat deforestation and improve water management. To address these challenges, Guatemala needs a multi-faceted approach that combines technological innovation with social and economic reforms. While a skilled workforce is essential for driving sustainable development, it is equally important to address underlying issues such as corruption, inequality, and weak governance. Creating opportunities, jobs, and investing in all levels of education, particularly in science and engineering, can help equip the country with the necessary human capital to develop and implement innovative solutions.

## Honduras

Honduras faces significant hurdles in its scientific and technological advancement (Bonilla et al., 2022). Decades of insufficient funding and inconsistent government policies have hampered progress. The National System of Science, Technology, and Innovation (SNCTI) lacks integration between government entities, universities, and other sectors, further hindering effective development. While initiatives like Honduras Global (HG) engage the scientific diaspora, broader policies are needed to fully leverage their expertise.

## El Salvador

El Salvador has seen a shift toward procedural democracy in the last few decades, with competitive political parties and peaceful transfers of power. However, further efforts are crucial to strengthen institutional protections for indigenous citizens (Gellman and Bellino, 2019). While this political progress is noteworthy, the country faces significant challenges in its educational and scientific development. Structural educational issues, such as low quality and inadequate teaching standards, obstruct scientific development in El Salvador (Picardo Joao et al., 2020; Picardo Joao, 2004). A preference for migration over higher education due to better remuneration prospects creates socio-economic ramifications.

## Nicaragua

The institutionalization of science in Nicaragua began in the 1980s with strong support from Nordic countries, particularly Sweden. The 1990s saw further development with the creation of research institutes within public and private universities, particularly the University of Central America (UCA). However, as a developing nation facing poverty, research often focused on immediate challenges, hindering long-term strategic initiatives. Now, the situation is dire. A sociopolitical crisis fueled by reported government abuses [(United Nations High Commissioner for Human Rights (UNCHR), 2024)] has devastated Nicaragua's academic landscape. The closure of over half its universities, including UCA and the Academy of Sciences, has crippled scientific infrastructure and threatens academic freedom (Karath, 2023). Restoring academic freedom, fostering international collaboration, and strategically investing in research focused on long-term sustainability are crucial steps for Nicaragua to rebuild its scientific capabilities and address its pressing challenges.

## Costa Rica

Despite its robust scientific infrastructure and notable integration of STI policies into national development plans, Costa Rica faces challenges in fully capitalizing on science and technology for social and economic progress. The country grapples with substantial infrastructure deficiencies, particularly in transportation and water treatment, further strained by a significant fiscal deficit. Being a small, open economy, Costa Rica is highly vulnerable to external shocks like global inflation, weakened global growth, and tightened financing. Climate vulnerabilities, intensified by El Niño, add to these uncertainties. However, Costa Rica stands out from its Central American peers. It has a thriving startup scene across diverse sectors like software development, artificial intelligence, renewable energy, and biotechnology (Jarquin-Solis and Mauduit, 2021).

## Panamá

Panamá's recent science diplomacy success offers a model for Central America. By integrating scientific advice, they

tackle complex regional challenges in health, agriculture, and the environment. This leadership paves the way for other small countries to excel in science diplomacy. However, Panamá grapples with a trend where PhD graduates seek opportunities abroad due to limited local prospects. Challenges include external funding dependence, limited research engagement in universities, and a critical lack of funding from the business sector. Weak governance calls for collaborative efforts to fortify the STI system (Gittens et al., 2021).

# National innovation systems and regional dynamics of STI in Central America

Following the challenges faced by each Central American country, as outlined above, it is important to explore the broader frameworks and emerging trends shaping STI in the region. Countries such as Costa Rica and Panama offer more established systems that could model pathways for others, yet Central America as a whole requires deeper regional collaboration and policy consistency to overcome shared barriers to STI-driven sustainable development.

## National innovation systems

Central American countries present contrasting scenarios in their STI development. While Costa Rica and Panama, have established relatively robust STI frameworks, others struggle to sustain systems that can effectively support scientific research and innovation. Institutional structures for science and technology were set up across Central America starting in the early 1990s, with Costa Rica (1990), Guatemala (1991), El Salvador, and Panama (1992), and Honduras (1993) enacting regulations to create foundational innovation systems (Viales-Hurtado et al., 2021). Nicaragua, however, was slower to act, with a research promotion structure established in 1995, only becoming operational in 2000 (Huete-Pérez, 2008). By contrast, most other Latin American countries had already developed National Research Councils by the 1950s (Crespi and Dutrénit, 2014).

Today, Costa Rica leads the region with a mature National Innovation System supported by policies that foster innovation across public and private sectors, particularly in clean energy and biodiversity conservation research. Similarly, Panama has established a robust framework through its National Secretariat of Science, Technology, and Innovation (SENACYT), overseeing policies that emphasize knowledge creation in health and agriculture and benefiting from both government funding and foreign investment. In contrast, Nicaragua, Guatemala, Honduras, and El Salvador share common structural challenges, including institutional fragmentation, limited research and development (R&D) funding, and insufficient policy continuity (Padilla Pérez et al., 2012). Their STI activities remain concentrated in under-resourced government agencies and a few public universities, relying heavily on regional initiatives to supplement national capacity (Bovenschulte, 2010).

## Intersectoral collaboration

The effectiveness of intersectoral collaboration varies significantly across the region, with Costa Rica and Panama demonstrating relatively strong cross-sector partnerships. Costa Rica's private sector actively contributes to STI funding, particularly in clean energy and biotechnology, while Panama has formed alliances with international research centers that align academic research with industry needs. This cross-sectoral engagement bolsters the scientific capacity of these countries and provides a model for leveraging both domestic and foreign expertise.

In contrast, intersectoral collaboration in Nicaragua, Honduras, El Salvador, and Guatemala is more limited, with government and academic institutions often working in isolation from the private sector (Viales-Hurtado et al., 2021). This limited coordination leads to mismatched priorities between STI initiatives and community or industry needs. However, regional organizations such as the Central American Integration System (SICA) and the Economic Commission for Latin America and the Caribbean (ECLAC) have introduced collaborative frameworks to strengthen partnerships and resource-sharing across the region (Peralta Quesada and Padilla Pérez, 2019). These frameworks aim to build unified research agendas that reflect the region's needs and are essential for tackling shared challenges in areas such as climate change and public health.

## Policy and institutional frameworks

Policy frameworks across Central America reflect diverse levels of engagement and resource allocation toward STI. Costa Rica and Panama have adopted well-coordinated policies, including tax incentives for research and development, which attract investments and drive innovation. In contrast, other countries continue to face policy inconsistencies and limited budgets. Addressing these issues, SICA and ECLAC advocate for consistent STI policy integration across Central America, with the Central American Innovation Agenda pushing for policy support in areas of strategic importance such as climate adaptation, STEM education, and health (Padilla, 2013).

Science diplomacy has also emerged as a key strategy, particularly for resource-constrained nations. Through foreign partnerships, Honduras and Nicaragua may gain access to technical expertise and advanced research that supports national STI goals, helping address critical gaps in health and environmental resilience.

## Emerging trends

Across Central America, emerging trends indicate promising advancements in STI. Digital transformation and increased investment in biotechnology and renewable energy are gaining momentum, especially in Costa Rica, Nicaragua and Panama. The region is also seeing a growing emphasis on research diversity and climate adaptation strategies, with initiatives that recognize the value of indigenous knowledge systems as part of sustainable development.

As these trends take shape, regional integration remains essential to ensure equitable progress across countries with different levels of STI maturity. The initiatives in Costa Rica and Panama illustrate effective models that other nations can draw from, while regional organizations provide the frameworks needed to drive collective action and overcome persistent challenges like funding constraints, institutional fragmentation, and policy inconsistencies. This integrated approach is crucial for building a resilient, STI-driven future across Central America.

## Fostering opportunities for early career researchers in Central America

Recognizing the critical role of human capital, the workshop also explored ways to empower early career researchers (ECRs) in Central America. A strong scientific workforce is fundamental for harnessing Science, Technology, and Innovation (STI) for sustainable development. This section delves into the GloSYS project by the Global Young Academy (Nieto et al., 2022).

GloSYS, extending beyond a global initiative, carries specific relevance for Central America's scientific landscape. It thoroughly investigates the educational, experiential, and aspirational dimensions influencing ECRs in the region, identifying critical constraints such as job precarity, financial insecurity, bureaucratic hurdles, language prominence, and the intricate balance between career and personal goals. Furthermore, it is essential to address these challenges by increasing access to higher education, providing adequate funding for research, and creating supportive research environments that encourage innovation and critical thinking, factors that are relevant to foster a thriving research culture in the region.

ECRs are caught in a double bind: a brutal job market and crippling financial insecurity. Short-term contracts, fierce competition, and stagnant salaries leave them stressed, uncertain, and often questioning their abilities. Their passion for research clashes with the harsh reality of a system that fails to support their scientific ambitions. This situation demands immediate attention and policy changes to nurture the next generation of scientific leaders in the region and beyond (Nieto et al., 2022). To cultivate a prosperous scientific culture, it is essential to address systemic challenges such as inadequate infrastructure and a lack of mentorship opportunities. Nurturing interdisciplinary collaboration and promoting public engagement are essential steps toward creating an environment that fosters innovation, critical thinking, and scientific excellence.

The GYA's leadership program for early career scientists, exemplified by an event in Leticia, Colombia in December 2022, stands out as notably significant. Held strategically outside a capital city, this highlights the project's commitment to diverse and inclusive representation, crucial in regions like Central America (Rondón-Jara et al., 2024).

The most recent GloSYS report meticulously addresses the challenges confronting ECRs in Latin America and the Caribbean. Issues like underfunded research systems and deficient infrastructure contribute to problems such as the absence of permanent employment prospects and non-remunerated work. The report doesn't merely diagnose these challenges; it also proposes mitigation strategies.

GloSYS, an ongoing research initiative, actively seeks collaboration with academic and research institutions in the region, extending an invitation to young scientists in Central America to play an active role in shaping their careers and contributing to the broader global scientific discourse. As the project advances, its outcomes have the potential to inform policies and initiatives that positively impact the trajectories of early career researchers in Central America.

By fostering a more supportive environment for ECRs, as outlined by GloSYS' recommendations, Central American nations can harness the full potential of their scientific workforce for sustainable development.

## A path forward: key actions for a sustainable future based on STI

Based on the findings from the international workshop, we present the following roadmap as a comprehensive overview of the current state of STI in Central America, along with actionable recommendations to address key challenges and opportunities. These insights aim to guide policymakers and stakeholders in developing robust strategies to overcome the region's specific barriers to STI progress. The main findings have been categorized into four key areas—structural challenges, sociopolitical and environmental issues, education and human capital development, and innovation and energy transformation—and are outlined in Tables 1–4. Notably, a discussion on the critical issue of budget allocation in universities across the region is included, highlighting that the majority of funds are directed toward teaching rather than research. This imbalance represents a significant structural challenge to advancing STI capabilities in these nations. Each table provides targeted recommendations that address the unique needs and opportunities within these categories, offering a clear path forward for sustainable development in the region.

Furthermore, to foster an environment conducive to STI advancement in Central America, comprehensive policy reforms are urgently needed. These reforms should prioritize investments in education—particularly at the graduate level—and involve curriculum updates that emphasize research skills and critical thinking. Additionally, policies should focus on creating supportive research environments through adequate funding, mentorship, and opportunities for collaboration. Adopting a holistic approach that addresses the multifaceted challenges facing the region is essential, considering the following areas:

### At the core of this strategy is the transformation of the educational landscape

Policymakers must focus on improving teaching standards and quality across all educational levels, with a particular emphasis on incentivizing higher education in Science, Technology, Engineering and Math (STEM) fields. This educational revitalization should be

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TABLE 1 Structural challenges and innovation systems in Central America.

| Challenges | Actionable interventions |
|---|---|
| Lack of institutional framework for global knowledge economy participation | STI policies should account for historical and social contexts, adapting structures to promote research and sustain innovation for post-industrial growth |
| Insufficient financing, poor institutional coordination, limited academia-industry collaboration, and inadequate STI indicators | Prioritize investments in STI with adequate state funding and coordinated fiscal policies. Engage governments, trade groups, and civil society to align efforts with the UN SDGs through impact investments by 2030. Explore sectors beyond Medical Sciences to include biotechnology |
| Limited understanding of innovation systems in less developed countries, including the transition from traditional goals toward broader national challenges | Realign STI policies to target complex national issues, adopting frameworks tailored to regional realities. Develop comprehensive policies to drive innovation, strengthening institutional frameworks and stakeholder coordination |
| Insufficient public investment in science and research, hindering the development of knowledge societies in Central America | Central America should allocate a minimum of 1% of GDP for science and technology. Each country should establish at least one research university and create national research institutes regionally. Collaborative science and technology parks with universities are vital for strengthening innovation ecosystems |
| Disproportionate allocation of university budgets toward teaching over research in many Central American countries | Implement policies to gradually increase the proportion of university budgets allocated to research activities, while maintaining educational quality. Encourage partnerships with industry and international research institutions to supplement research funding |

TABLE 2 Sociopolitical and environmental challenges in Central America.

| Challenges | Actionable interventions |
|---|---|
| Sociopolitical challenges, such as migration, gender violence, and authoritarianism, which undermine democratic and economic development | Promote collaborative research and science diplomacy, leveraging global partnerships for STI. Focus on evidence-based policymaking to address root causes of migration and violence, particularly in the Northern Triangle |
| Censorship and attacks on environmental scientists and activists, particularly in regions like Nicaragua's Mayangna Sauni. As territory, which weaken scientific systems and limit investment | Develop national policies to protect environmental scientists, activists, and vulnerable communities. Strengthen law enforcement and prioritize indigenous rights in Mayangna Sauni As. Nicaraguan authorities must uphold Inter-American Human Rights protections, ensuring culturally sensitive consultations with indigenous populations |
| Transition from a destructive, business-as-usual model to one driven by STI for sustainable development | Establish robust strategies for sustainable growth, focusing on education, climate resilience, and Ph.D. initiatives. Strengthen regional collaboration and prioritize comprehensive planning for environmental and societal challenges |

TABLE 3 Educational and human capital development.

| Challenges | Actionable interventions |
|---|---|
| Disconnection between the scientific community and policymakers, hindering the development of effective solutions | Establish governmental scientific advisory bodies to bridge scientists and policymakers. Provide training at the science-policy interface to improve mutual understanding and communication |
| Nicaragua faces severe threats to academic freedom and institutional autonomy, with the closure of over half its universities, including the Jesuit University of Central America and the Academy of Sciences of Nicaragua | Implement measures to safeguard academic freedom and institutional autonomy in Nicaragua. Focus on reopening universities, including the Jesuit University of Central America, and ensuring long-term stability in higher education. In doing so, there may be opportunities for science diplomacy to play a role in fostering dialogue and cooperation between relevant stakeholders in the region |
| Low educational quality, high dropout rates, and insufficient state policies in scientific and technological education | Implement long-term educational reforms to improve school quality and retention rates. Ensure sustained investments in science education across Central America |
| Lack of early-career scientist engagement in policymaking due to limited awareness of opportunities and resources | Encourage scientists to join fellowships and professional societies that offer policy training. Support community outreach, science communication, and evidence-informed policymaking |

TABLE 4 Innovation and energy transformation in Central America.

| Challenges | Actionable interventions |
|---|---|
| Immense energy challenges as demand is forecasted to grow significantly by 2050 | Develop STI policies in areas like smart metering and digital transformations in the energy sector. Promote energy efficiency and conservation in buildings and transportation through sector-specific energy plans and technology standards |
| Agricultural technology focused on high-income countries, reducing its effectiveness in addressing Central American needs | Redirect agricultural investments to address local challenges and ensure that agricultural technology aligns with the region's specific needs. Funders (both public and private) should play a vital role in supporting this transformation |

coupled with the creation of research-oriented technological hubs and centers nationwide, bridging the gap in graduate programs focused on scientific research.

## Collaboration is key to this transformation

Fostering partnerships between Central American countries, incentivizing student exchanges, and developing connections with international institutions can significantly enhance knowledge transfer and STI capabilities. Moreover, a comprehensive policy promoting public-private partnerships is essential. This approach will encourage collaboration between universities,

research institutions, private sector companies, and international organizations, driving the development and implementation of innovative technologies crucial for addressing pressing issues such as environmental sustainability.

## Government action plays a pivotal role in this roadmap

Prioritizing research through concrete measures and investments in education can propel national progress and prosperity. Additionally, offering fiscal incentives for companies investing in innovation could catalyze private sector involvement in STI development. To implement these recommendations effectively, we propose the following specific actions:

## Prioritizing research

Establishing a National Research Fund that allocates a dedicated percentage (e.g., 1%−2%) of the annual national budget to research initiatives is a key step. This fund should be overseen by an independent council of experts responsible for evaluating and distributing resources based on national priorities and scientific merit. Additionally, implementing a competitive grant system can promote innovative projects aligned with the country's development goals, ensuring that funding is directed toward impactful initiatives.

## Investing in education

To cultivate a robust STI ecosystem, it is imperative to invest in education and research. A comprehensive STEM education strategy, from primary to tertiary levels, is essential to nurture a skilled workforce. This includes introducing coding and digital literacy programs early on and fostering partnerships with international institutions to enhance curriculum and faculty development. Additionally, creating competitive research institutions and incentivizing innovation can drive scientific advancement and technological breakthroughs.

## Fiscal incentives for innovation

To stimulate private-sector investment in innovation, governments should introduce targeted fiscal incentives for companies that invest in research and development (R&D). Measures could include tax credits for businesses dedicating a specific percentage of revenue to R&D and offering accelerated depreciation for investments in innovative technologies and equipment. Additionally, governments should create regulatory environments that are conducive to innovation, such as streamlined approval processes for new products and services.

## Private sector involvement

Increasing private sector involvement can be achieved through tailored public-private partnership (PPP) frameworks for STI projects. These partnerships can promote collaboration between academia, industry, and government to collectively address national challenges. Innovation hubs that bring together researchers, entrepreneurs, and established companies can further foster an ecosystem of knowledge transfer and commercialization. Additionally, mentorship programs linking startups with experienced companies will enhance innovation by providing the necessary guidance and resources for success.

## Strengthening regional collaboration

Establishing a Central American STI Network would enable resource pooling, knowledge sharing, and collaboration across the region. A digital platform could connect researchers, facilitate project collaboration, and streamline knowledge dissemination. A regional mobility program for researchers and students would further support knowledge exchange, while annual STI conferences would showcase regional research and foster partnerships. Joint funding mechanisms for cross-border research on shared challenges, along with regional centers of excellence in fields like tropical diseases and sustainable agriculture, would enhance collective STI capabilities. Integrating with ACAL-Conecta could also join Central American researchers with broader Latin American networks, creating economies of scale and expanding research impact. To build on these initiatives, the model of Nicaragua's Biotechnology Conferences, organized by the UCA Molecular Biology Center, offers an effective example (Huete-Pérez et al., 2012). Since 2000, these biennial events have connected academia, industry, and government, promoting biotechnology research, addressing regional needs, and fostering innovation opportunities. This approach strengthens national and regional scientific networks, advancing public-private partnerships and research infrastructure. Adopting a similar model within the proposed Central American STI Network could significantly enhance collaboration and development across the region.

By implementing these specific actions, governments can create an environment conducive to STI development, fostering a culture of innovation and driving economic growth. Regular monitoring and evaluation of these initiatives will be essential to ensure their effectiveness and facilitate adjustments as needed.

While these broad strategies provide a regional framework, it's crucial to recognize that each country faces unique challenges requiring tailored approaches. Guatemala needs to prioritize environmental sustainability initiatives, while Honduras should focus on implementing consistent STI policies. El Salvador's primary focus should be on improving educational quality, and Nicaragua must work toward restoring academic freedom. Costa Rica can build on its strengths by further leveraging its thriving startup ecosystem, while Panama should develop strategies to retain its PhD graduates and curb brain drain.

By implementing these interconnected strategies—educational reform, collaboration, government support, and country-specific

initiatives—Central America can pave the way for a brighter future, harnessing the power of STI to drive sustainable development and improve the lives of its citizens.

## From challenges to opportunities

Despite challenges, collaborative social science research across Nicaragua, El Salvador, and Guatemala highlights the transformative potential of regional cooperation. Costa Rica's successful startup scene in sectors like renewable energy and biotechnology further demonstrates the region's potential for innovation.

To unlock the potential of STI in Central America, strategic policy frameworks tailored to each country's needs are crucial. Sustained financial investment in research and development is essential for long-term growth. Currently, Central American countries invest only a small percentage of their GDP in R&D compared to developed nations. Increasing this investment to around 1% of GDP could be a realistic target to foster regional innovation, attract talent, and create high-value jobs.

While developed economies like the United States, the European Union, and South Korea allocate 2–4% of GDP to R&D, Latin American and Caribbean countries fall behind, with regional investment decreasing from 0.7% to 0.6% of GDP between 2015 and 2021 (ECLAC, 2024). According to UNESCO, Costa Rica invested 0.39% of its GDP in R&D in 2018, El Salvador 0.16%, Panama 0.13%, Guatemala 0.03%, and Honduras 0.04% (Lewis et al., 2021), while recent data for Nicaragua remains unavailable. This stark disparity highlights the urgent need for increased R&D funding to drive sustainable development and innovation in Central America.

Boosting public R&D investment not only supports technological advancement but also strengthens economic growth, job creation, and quality of life. By aiming for 1% of GDP in R&D spending, Central American countries can enhance their global competitiveness and promote inclusive economic growth that benefits a broader spectrum of society.

Furthermore, fostering collaboration between universities, research institutions, and the private sector is vital to leverage resources and expertise. By addressing regional challenges, implementing strategic policies, and fostering collaboration, Central America can harness science and technology to drive sustainable development and improve the lives of its citizens.

## Discussion

The dynamic landscape of Science, Technology, and Innovation (STI) policies in Latin America underscores an urgent demand for robust analytical frameworks to address national challenges. There is a discernible shift from traditional National Innovation System (NIS) approaches to problem-oriented paradigms, advocating for holistic policies that intricately consider the systemic nature of challenges (Ghazinoory et al., 2020). This shift stresses the adaptability of effective STI policies, placing particular emphasis on governance mechanisms to navigate complexity and highlighting the indispensable role of end-users in the policymaking process (Alvarez et al., 2020).

Central America's National Innovation Systems are evolving, presenting both opportunities and challenges for sustainable development. Looking ahead, the region's STI development hinges on several critical factors: strengthening institutional frameworks, fostering sustainable funding mechanisms, and most importantly, engaging youth in STI leadership. This focus on youth engagement is particularly crucial as it represents both an emerging trend and a key strategy for long-term development. These efforts must carefully balance innovation goals with social cohesion needs, recognizing that sustainable development requires both technical advancement and social stability. The diverse experiences across Central America, from the more advanced systems of Costa Rica and Panama to the emerging frameworks in other nations, offer valuable insights for developing nations facing similar challenges in building effective National Innovation Systems.

The responsibility of science communicators is underscored, emphasizing the need for scientists to engage in culturally relevant communication and research translation (Cumba García, 2020, 2021). Importantly, complex, and adaptive actions are needed to address intricate problems, with a particular emphasis on the teachability and learnability of science diplomacy and the science-policy interface. Collectively, this discussion illuminates the multifaceted nature of STI policies in Latin America, advocating for adaptive, inclusive, and holistic approaches to drive transformative advancements and, crucially, to empower the next generation of scientists.

Drawing insights from the Mexican experience, the discussion extends to the pivotal role of educational institutions in nurturing emerging scientists. Amendments to Science, Technology, and Innovation Policies (STIP) in Mexico are underscored, emphasizing the significance of the Science Policy Interface as a social process involving scientists and policymakers (Van den Hove, 2007). The discussions identified a transformative shift from "science-based" to "science-informed" policies, challenging cultural perceptions and emphasizing inclusivity in scientific input in policy considerations.

Concrete examples include the amendment for incentives to create spin-offs based on science (Hernandez-Mondragon et al., 2016) and the Mexico City Science Policy Fellowship. The fellowship provides researchers with a valuable opportunity to directly influence policymaking at both national and international levels (Hernández-Mondragón, 2022). The discussions placed significant importance on the involvement of scientists in evidence-informed policymaking, stressing proactive outreach and engagement in third-sector organizations. Strategies for science policy career preparation, including fellowships, partnerships, and policy and diplomacy training, are relevant (John et al., 2023).

The Mexican experience highlights the importance of adapting STI policies to the evolving landscape (Natera et al., 2019). Central American countries could consider adopting a flexible policy framework that can accommodate changes in technology and address emerging challenges (Hernández Mondragón and Castañeda Hernández, 2023). This adaptability should extend to governance mechanisms, ensuring the policies remain effective in navigating complexity. Encouraging active collaboration and

dialogue between the scientific community and policymakers can lead to more informed and inclusive policies (Dutrénit et al., 2018).

Examining the challenges and lessons in Colombian science and technology offers insights applicable to Central America. Historically reliant on imported technology, Colombia's pivotal step in 1968 with the creation of Colciencias marked a commitment to impactful policies. Successful initiatives, such as the Caldas Network and technology development centers, highlight positive strides (Montoya and Rivera, 2013; Chaparro et al., 2016). However, the need for skilled individuals remains a challenge, emphasizing the importance of investing in human capital.

Recent shifts, including Colciencias becoming a ministry in 2019 and efforts to promote South-South collaboration, are notable. Yet, projected budget reductions for science and technology in 2024 and issues like companies prioritizing technology over knowledge pose obstacles. Comparisons with developed countries underscore the urgency of increased R&D investment. Advocating for long-term programs, human talent development, consistent government support for research institutions, and effective governance are crucial for overcoming future challenges.

Despite the Colombian Academy of Sciences' instrumental role, the country's STI investment remains modest at 0.29% of GDP (World Bank, 2024), contrasting sharply with the US. This serves as a reflective guide for Central America, emphasizing the need for strategic and sustained investments in science and technology.

The experiences of other Latin American countries offer valuable insights into effective STI policy implementation. Argentina's strategic focus on key sectors such as biotechnology and nuclear energy, coupled with its emphasis on international collaborations, has significantly enhanced its scientific output and technological competitiveness (Albornoz and Gordon, 2011). Chile has emerged as a regional leader in astronomy by investing in world-class facilities, which has not only advanced scientific knowledge but also boosted science education and tourism (Guridi and Pertuze, 2020). Brazil's approach of fostering public-private partnerships in research and development has led to notable innovations, particularly in sustainable agriculture and energy production (De Negri and Squeff, 2016). These diverse strategies demonstrate the importance of targeted investments, international cooperation, and industry collaboration in driving STI progress. By examining these varied approaches alongside the experiences of Mexico and Colombia, we can gain a more comprehensive understanding of effective STI strategies in the Latin American context, providing valuable lessons for other countries in the region seeking to enhance their innovation ecosystems.

Furthermore, Central America requires with urgency comprehensive interventions to mitigate the escalating food insecurity crisis in Central America, where food security has reached its highest rate in the past two decades, affecting 19 million people (10.6% of the population). The Caribbean and South America also experience significant food insecurity, with 7 million and 33.7 million people affected, respectively (World Bank, 2021). Recent studies, such as the one by Benites-Zapata et al. (2021), highlight the severe impact of the COVID-19 pandemic on food security in Latin America and the Caribbean, emphasizing the role of sociodemographic factors and pandemic-related variables.

Addressing food security challenges in Central America requires a strategic focus on technological innovation within agri-food systems, involving both public and private sector efforts. Currently, public investment in agriculture is insufficient, and although private sector investment is higher, it still falls short of what is needed. Agricultural technology, predominantly designed for high-income countries, has proven less effective in regions like Central America, where only 58% of global agricultural productivity is achieved. Therefore, it is essential to redirect existing agricultural investments to address local challenges, while simultaneously increasing overall investment levels to meet the growing global demand for food and the rising production costs.

Science, Technology, and Innovation (STI) policies play a central role in this transformation, with governments needing to lead through cost analyses to make informed decisions on sectors that require increased investment or strategic reallocation. Funders also emerge as key stakeholders, capable of facilitating and supporting these shifts. The discussion highlights the urgent need for a nuanced and strategic approach to tackling food security challenges, harnessing technological innovations supported by robust STI policies to offer sustainable and inclusive solutions that can address regional challenges while contributing to global agricultural productivity.

The workshop also explored methods for evaluating key STI policies in Central America, specifically focusing on their applications in energy conservation. These encompass energy-efficient appliances, demand-side management, and sector-specific energy plans.

Highlighting the significance of innovative evaluation methodologies, the workshop addressed STI policies targeting energy conservation and behavior change in the Central American context. The central role of policy interventions in energy-related sectors like buildings and transportation was stressed to manage increasing energy consumption and achieve regional energy transition goals. The workshop delved into practices such as using Randomized Control Trials to establish causal links between innovation strategies and social impacts, revealing challenges related to voluntary participation in STI policies. Real-time appliance-level, environment, and health-based information strategies were found to be more effective than monetary savings information in driving energy conservation (Asensio and Delmas, 2015).

Throughout the discussions, there was consistent emphasis on the importance of policy interventions in critical energy-related sectors. The workshop advocated for leveraging behavioral strategies through information technologies as effective components of sustainable development pathways. Crucially, these strategies do not demand extended lead times typical of new capital investments in energy infrastructure. These insights offer valuable considerations for shaping impactful policies in the context of Central America's energy conservation efforts, advancing our understanding of the effectiveness of information-based conservation policies.

The workshop delved into the vital concepts of capacity and resilience in community development, emphasizing the imperative to train decision-makers and practitioners. This is essential to

address the dynamic nature of communities, requiring innovative capacity-building strategies and technologies.

Human development's linkage to global peace and security necessitates successful and resilient innovation ecosystems. These ecosystems should benefit people by ending poverty and hunger, ensuring dignity and equality. They should also protect the planet, preserving natural resources and climate for future generations. Achieving these goals requires solid global partnerships with businesses, contributing to prosperous lives in harmony with nature for more enduring peace.

Central America's aim is to promote sustainable, healthy, stable, equitable, safe, and prosperous communities. However, this is challenging in our fast-paced, uncertain, ambiguous, and complex world with interconnected processes and variables.

The workshop underscored Central America's potential to be a regional leader in Engineering, Science, Technology, and Innovation (ESTI) education. To achieve this, developing strength and capacity in ESTI is crucial for addressing sustainable development needs and fostering a global knowledge and skill-based economy. The focus is on training today's youth with the necessary skills to tackle global challenges. Initiatives such as Engineers without Borders in San Pablo, Belize, exemplify collaborative efforts between university students, engineers, and business owners to address challenges. The goal is to train a new generation of engineers and scientists not just as technical providers but as change-makers, peace-makers, and facilitators of sustainable human development. This training is vital for handling the spectrum from crisis to development, especially in the face of increased disasters over the past 20 years.

To formulate regional plans for ESTI in Central America, understanding how development problems are addressed by various constituencies (academia, industry, government, and civil society) is crucial. Training workshops can facilitate the review of these problems and the development of educational curricula addressing both regional and in-country challenges.

The discussion prompted reflection on integrating science into development problem-solving, echoing Einstein's perspective that the significant problems of today require a higher level of thinking than when they were created.

## Workshop regional and global significance

Central America, particularly in the Northern Triangle, faces persistent challenges leading to migrations driven by issues like poverty, violence, and corruption. The perilous journey through the Darién jungle poses threats, impacting migrants' wellbeing with risks ranging from injuries to violence. Territorial disputes, as seen with Nicaragua, add complexity to the region's dynamics. These formidable difficulties have profound implications for sustainable development in the area, hindering progress and resilience.

Science diplomacy may serve as a potent means to connect nations amid political tensions, fostering collaboration and mutual understanding, even in the face of strained relations and a tumultuous history (García et al., 2024). Utilizing science diplomacy emerges as a strategic approach to address these multifaceted problems, promoting collaborative solutions for poverty alleviation, violence prevention, and conflict resolution. International scientific cooperation, including exchanges, joint research initiatives, and knowledge-sharing, becomes instrumental in evidence-informed policymaking and sustainable development practices. This approach enables the region to harness collective expertise, fostering resilient innovation systems that tackle the root causes of migration and contribute to long-term stability and prosperity.

The workshop facilitated collaboration among scholars, policy experts, and researchers from Central America and the United States, exemplifying the application of science diplomacy to address common global and regional challenges. These challenges include sustainable development and advancements in science, technology, and innovation (STI). The engagement of experts from diverse backgrounds promoted international cooperation and understanding, showcasing the role of science in diplomacy by providing advice and evidence for decision-making in regional affairs. This collaborative model serves as an example of how countries with varying levels of scientific development can unite to enhance global knowledge sharing. For developed nations, it offers insights into supporting less-developed nations in their scientific endeavors, while developing nations can benefit from the experiences of more advanced counterparts, contributing to a balanced global science landscape.

The findings from this workshop can inform international organizations and development agencies working with less developed countries worldwide. Lessons about crafting effective science, technology, and innovation (STI) policies in resource-constrained environments can be applied globally, encouraging more countries to prioritize STI as a catalyst for progress.

# Conclusion

The international workshop served as an effective forum for fostering discussions, presentations, and the exchange of knowledge pertaining to science, technology, and innovation (STI) policies, innovation systems, and scientific advancements in Latin America, focusing on Central America. Its overarching goal was to facilitate and expedite sustainable growth while enhancing the quality of life in the region. The valuable insights and recommendations that emerged from the workshop carry the promise of fortifying STI policies and innovation systems in Central America, thus advancing the cause of sustainable development. The implications of this workshop extend beyond regional borders. They bear relevance to the broader context of global science diplomacy, and concurrently address the specific challenges confronted by Central America.

Central America grapples with limited resources and inefficient national innovation systems. This workshop brings together regional stakeholders to address these challenges. Lessons from this event can help Central American nations better utilize their available resources for STI. The emphasis on diversifying the research landscape is particularly relevant to Central America, where many nations have faced stagnation in researcher numbers. By following the example of countries like Costa Rica and Panama, which prioritize research diversity, Central American nations can revitalize their research ecosystems. The workshop highlighted a

critical issue in Latin America, also pertinent to Central America: the gap between the scientific community and policymakers. To address this, the establishment of governmental scientific advisory bodies was proposed, aiming to enhance the relevance and impact of STI policies in the region. See Table 3.

The discussions emphasized the transformative potential of the youth, the necessity to comprehend scientists' perspectives, and the influential role of leadership and diaspora in utilizing knowledge for national benefit. Challenges, including a reliance on individuals over institutions, the weakening of universities, and the departure of scientists, were acknowledged. Additionally, the dialogue underscored the importance of resilience, motivation, and presenting a compelling vision for the future. These aspects transcend political shifts, fostering interdisciplinary, long-term pursuits that inspire hope and progress.

Key takeaways from the workshop emphasize the imperative for Central American nations to invest in science-related education to cultivate the essential human capital for tackling climate-related challenges. The discussion advocates for proactive measures such as improving educational quality, incorporating scientific values into cultural narratives, and fostering a distinct national identity to attract knowledge and talent.

The workshop emphasized the significant role of biotechnology, especially in healthcare, as a potentially crucial sector for the region. Leveraging the strengths of biotechnology could further advance the bioeconomy, encompassing bioenergy, waste reuse, and agro-industry. This strategic shift toward the bioeconomy offers a pathway to tackle challenges associated with economic dependence on primary commodities (agriculture, mining, fossil resources), fostering diversification and structural change while mitigating instability stemming from price volatility.

Furthermore, the workshop emphasized the significance of adaptation to climate change and improved energy conservation efficiency. Given that Central America is highly vulnerable to climate change, leveraging science, technology, and innovation is vital for achieving sustainable development. The workshop's focus on energy conservation and behavior change has direct implications for Central America's energy transition. As per capita energy consumption increases, Central American countries need to adopt energy-efficient technologies and develop clear STI strategies for a sustainable future.

The workshop served as a catalyst for global science diplomacy, bridging the gap between developed and developing nations. Its findings and recommendations can significantly impact Central America by addressing resource constraints, promoting diversified research, strengthening science-policy connections, and providing guidance for sustainable development in the face of climate change. The workshop demonstrated how collaborative global efforts can drive meaningful progress in science, technology, and innovation.

In organizing this workshop, we aimed to ensure broad representation of perspectives, positions, and visions from various stakeholders across the region, including scholars, academies, and representatives from diverse countries. However, we acknowledge that the scope of our discussions is inherently limited by the financial resources available to convene stakeholders from all the nations involved. Despite these constraints, we believe this work offers valuable contributions to the existing literature on STI policies and development in Central America. It is our hope that the insights and recommendations presented here will not only inform future policy decisions but also inspire further research and collaboration in this critical area.

## Author contributions

JH-P: Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing, Conceptualization. AH-M: Investigation, Writing – original draft, Writing – review & editing, Conceptualization. DM: Writing – original draft. LC: Writing – original draft. BA: Writing – original draft. ND: Writing – original draft. MA: Writing – original draft. OA: Writing – original draft. JB: Writing – original draft. SC: Writing – original draft. EH: Writing – original draft. ML-S: Writing – original draft. JM: Writing – original draft. FM: Writing – original draft. JN: Writing – original draft. OP: Writing – original draft. AR: Writing – original draft. HR: Writing – original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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# Social technology and rescue of native seeds in the Venezuelan Andes Páramo

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This study analyzes the recovery and conservation of potato landraces in the Venezuelan Andes Páramo, specifically in the Mérida region. Smallholder potato farmers in the Venezuelan Andes have been actively creating knowledge, processes, and socio-technical artifacts necessary for the recovery of potato seeds and other types of plant genetic resources critical for food and agriculture. This effort has involved diverse socio-technical dynamics, engaging both human and non-human actors, with the support of universities, research institutions, local and national governments, etc. These initiatives counter historical trends, such as the erosion of complex genetic resource systems, genetic resources, the impacts of agricultural modernization, dependency on oil and imported agricultural technologies, and more recent challenges, such as food shortages. Using traditional techniques such as *Tinopós*—underground caves for seed storage—and social appropriation of technological processes, including genetic improvement, Andean smallholder farmers have successfully rescued ancient potato varieties while developing new ones. Fieldwork conducted in 2019 included a documentary review, thematic analysis, and a technology inventory. The findings reveal a close relationship between the diversity of Andean root and tuber crops, the unique biophysical and climatic conditions of the Páramo, and the traditional knowledge of peasant communities residing in these territories. The study underscores the importance of border relations and cultural translation between different knowledge systems in recovering and conserving native potato seeds. These efforts represent a locally driven initiative to construct social technologies for food sovereignty and sustainable local development.

KEYWORDS

**social technology, production of knowledge, potato seeds, agroecology, agrobiodiversity, bottom-up public policy, scientific–peasant coalition, Venezuela**

## 1 Introduction

The Andes highlands are recognized as the center of origin of potatoes (*Solanum tuberosum L.*). Countries such as Peru, Bolivia, Ecuador, Chile, and Colombia have the highest potato landraces and its wild varieties (De Haan and Rodriguez, 2016). The Andes highlands is particularly significant for producing local potato varieties due to specific factors such as soil quality and high altitudes. The soil is rich in minerals such as phosphorus, potassium, calcium, and magnesium, while high altitudes (Tapia and Fries, 2007) create a temperature range that is warm during the day and very cold at night. This temperature variation reduces the likelihood of pests and diseases. Additionally, the development of ancestral sustainable management techniques, such as "tinopós" or "andenes" play a crucial role in producing potato varieties. These practices help retain water and prevent soil erosion, forming a part of

traditional agricultural systems. The ancestral knowledge of Indigenous people and traditional communities has led to the creation of different types of systems over pre-Columbian times to preserve or protect potato seeds in complex environments (Forbes et al., 2020). In this study, we explore the experiences of potato smallholder farmers from the Venezuelan Andes and their local technologies for the rescue of native potato seeds. To reflect on innovative possibilities for public policies, we analyze the production of potato seeds in two communities in Rangel municipality. We discuss its processes of cultural translation, i.e., effective horizontality in contexts of interface between diverse cultures, as a source of innovation.

Potato smallholder farmers from the Venezuelan Andes have carried out efforts to protect their native seeds and the social fabric, specifically in Mucuchíes, the capital of Rangel municipality in the state of Mérida. Like the rest of the Andes, mountain elevations exceed 3,000 meters, and the endemic vegetation, fauna, and a wide variety of crops have adapted to these climatic conditions. These small farmers have used hybrid systems involving social and ancient technologies, such as rescues of native potato seed and conventional genetic improvement. It made possible the development of local potato systems that have impacted regional and national potato seed systems (Romero, 2005). According to reports from the Ministry for Science and Technology -MINCYT, Spanish Acronym (2024), there are currently more than 200 groups of ancestral seed producers in Venezuela, impacting the increase in food production.

Since the 1960s, producers from the Rangel municipality have been participating in education programs, including technical assistance activities organized by governmental and non-governmental organizations at the local, regional, and national levels (Richer, 2005; Llambí, 2012). This process facilitated rebuilding a social fabric, where learning, adoption of practices and knowledge, and a specific capacity for resilience have been crucial in dealing with challenging circumstances such as the different socioeconomic crises of the country, as well as the socio-environmental conflict related to the uses of the Páramo (Richer, 2005; Romero, 2005). In 2003, the Productive Innovation Networks (Redes de Innovación Productiva-RIP, Spanish acronym) had an important role in the drive of social technology development. It was a public policy supported in the "Plan Nacional de Ciencia, Tecnología e Innovación. Construyendo un futuro sustentable Venezuela 2005–2030" (Ministry for Science and Technology, 2005) aimed at providing access to resources such as funding, marketing, training, and technical support to promote local development through innovative, productive activities, or grassroots innovations. For Mérida Andes *Páramo*, the Ministry encouraged the establishment of a specific innovation network to produce potato seeds (Red de Innovación Productiva de la Papa, RIP-SP, Spanish acronym), considering the region's tradition on potato production. Actors from diverse backgrounds participated in the RIP-SP, such as local farmers, local and national governments, universities, non-governmental organizations, community leaders, etc.

A long-standing debate recognizes the importance of technological appropriation or the development of appropriate technologies to solve socio-environmental issues in rural areas (Herrera, 1981). In recent decades, social technology (ST) has emerged as a specific category to identify initiatives, processes, and artifacts that originate from collective and democratic actions aimed at solving local problems or addressing rights violations stemming from socioeconomic, cultural, and symbolic exclusion (Tait, 2017; Silva and Dias, 2020), contrasting with conventional technology models that prioritize profit and scalability (Dagnino, 2009). "The concept of Social Technology emerges as a critique of conventional technology (CT) and from a perception, not yet precisely formulated, of the need for a technological approach to the issue of what has been called social inclusion" (Novaes and De Brito Dias, 2010: 113). In this sense, "social" refers not only to interactions between people and between them and things but also to the protagonism of local communities to solve socio-environmental and economic issues. Tait (2017) describes some characteristics of ST in a rural productive context, such as establishing horizontal relationships within the domestic market, fostering the potential and creativity of both producers and consumers and supporting economically viable initiatives such as community cooperatives, incubators, and small enterprises. In practice, social technologies are increasingly adopted in the context of agroecological practices and as a platform for producing diverse knowledge to understand the functioning of complex agroecosystems and global environmental governance (Altieri, 1998; Foyer et al., 2014). For instance, initiatives such as community seed banks or native seed houses in different regions of Brazil exemplify how social technologies can address seed scarcity by integrating traditional practices with productive knowledge and broader networks (Alves et al., 2023). Those networks comprise a wider diversity of external agents, assuming complex relationships that benefit from intercultural translation processes. Ribeiro (2005) explains that the concept of translation has shifted from linguistics to cultural studies, which has broadened its meaning. From this broad perspective, translation is "a keyword of our contemporaneity, a central metaphor of our time. Potentially, any situation in which one seeks to make sense out of a relationship with difference can be described as a translatory situation" (Ribeiro, 2005: 79). Therefore, through translation, it is possible to identify, within a heterogeneous environment, "common concerns, complementary approaches and insurmountable conditions" (Santos, 2002: 34). It is possible to amplify experiences because instead of focusing on rival knowledge, its focus is on creating mutual intelligibility (Ribeiro, 2005).

The translation is challenging because the subjects are walking on completely new ground (Santos, 2002). If the frame of reference is debated and redefined, then power relations are also called into question (Ribeiro, 2005). We argue that rather than transferring technologies from a hierarchical and verticalized perspective, social technologies based on translatory processes have the potential to break down hegemonic power relations and create new responses from the border space between different epistemic paradigms. Specifically, we focus on the experience of Gavidia Base Nuclei (NuBaSe) and Association Integrated Producers of the Páramo (Proinpa), which can be understood as processes based on intercultural translation.

## 2 Methods

We conducted a qualitative study, beginning with an exhaustive documentary review of local and regional literature to identify and analyze relevant cases and map social technologies. Subsequently, we collected empirical data through a visit to the Mucuchíes population center, the capital of the Rangel municipality, a community known for its potato seed production, and the location of Proinpa and

Gavidia Base Nuclei. We conducted 16 open conversations distributed to 5 women and 11 men. It followed a strategy of informal conversation, without adhering to traditional "subject/object" hierarchies, being selected randomly, and without responding to any statistical interest. These conversations took place as representatives of the organizations participated in arranging an event commemorating the twentieth anniversary of Proinpa in August 2019. All of them were farmers and producers of local potato seeds. Some were members of Proinpa, while others participated in the project to recover native seeds from the community of Gavidia.

Regarding the members of Proinpa, six identified themselves as founding members of the Association. Through these conversations, we explored the professional trajectories and their involvement in the Association's activities. Other field records were made during the event. It was evidenced that meeting places such as a cultural feast are necessary for preserving the communitarian social fabric.

The information was transcribed and systematized in a matrix created for this research. The statements of participants were read alongside the contributions of the documentary review to understand the different moments that characterize the process of rescuing native seeds in the context of the páramo de Mérida, the actors involved, and the dynamics that have been part of this process. On the other hand, the already systematized data were questioned to open the space for the emergence of new explanations.

Every person spoken to was informed that this was an academic investigation and that the information would be treated according to ethical guarantees (voluntary participation, participant integrity, and preservation of personal data).

# 3 Results

The inventory of ST was built with input collected in the bibliographic review, in pre-field conversations, and from inputs provided by an associate who was initially contacted and who paved the way for the research to be carried out (Table 1).

Gavidia Base Nuclei (NuBaSe) and the Biotechnology Center for the Training and Production of Agamic Seeds (CEBISA) are ST because they are solutions for socio-cultural, economic, and environmental issues. In addition, they were built for local populations acting in networks with different sorts of actors, challenging the conventional technological system for agriculture, as we will see below.

## 3.1 Gavidia base nuclei (NuBaSe) and the *EcoFestival* of the native potato

Although the populations of Gavidia have carefully preserved some potato landraces for domestic consumption, the experience of recovering and producing on a larger scale is relatively recent. It occurs in the context of the development of research co-produced with research groups from the University of Los Andes (ULA) and RIP-SP. A long research process was launched in 1985 to study the ecological conditions of the agricultural system in the Venezuelan Andes, with Gavidia playing a crucial role. Since then, several research communities at ULA have been involved in developing studies to gain a comprehensive understanding of agroecosystem dynamics based on farmers' sociocultural and economic practices.

In Gavidia, the Orchards, Caves, or ancient *Tinopós* continued to be a "source of new seed" of the Black Potato or Páramo Potato variety. These are considered native or ancestral potatoes stored in the farmers' farms in cycles of up to 25 years (Romero, 2005). The management of these crops was evidenced by the absence of treatment or cure for pests or diseases, and yields were improved through fertilization with livestock manure. However, resting lands resulted in more notable harvests (Romero and Monasterio, 2005). Storage occurred in natural spaces within the field or in rudimentary structures built manually. Transport was conducted "by muleback to the nearest population centers with greater economic activity, such as Mucuchíes in the case of Gavidia" (Romero and Monasterio, 2005, p. 118). Other research began to advance the preservation of native potato seeds and encourage the growth of farming activities with minimal environmental impact. A researcher and the farmers started a project to create "seed areas." These areas would represent local sociocultural practices and reflect the levels of agroecological specialization needed for a national potato seed system. The Seed Self-Management Nuclei (NuBaSe-Spanish acronym) project was developed to continue the native seed rescue.

According to the researcher from ULA, who co-led the development and implementation of the project, the overarching objective was to reconstruct the social and community fabric that has historically supported the preservation of native potato seeds for family consumption. To achieve this goal, the project aimed, among other initiatives, to revitalize oral traditions and promote the intergenerational transmission of knowledge from elders to younger generations. One of the key references that inspired this

TABLE 1 The stock of social technologies development in Venezuelan Andean Páramo for potato seed production.

| Social technology | Description | Social demand attended | Outputs |
|---|---|---|---|
| Gavidia Base Nuclei (NuBaSe) | It is a communitarian network for potato seed production. It could be native or improvement. The main goal is to constitute "seed areas" for building a common agenda for a national potato seed system. | Access to native or local potato seed is needed for the mitigation of genetic erosion and biodiversity loss, improvement of the local crop capacity, and guarantee of food sovereignty, local and national. | – Re-building of the social fabric and rescue of native potato seed.<br>– *EcoFestival* of the Native Potato of Venezuela.<br>– Expansion of NuBaSe at the national level (124). |
| Biotechnology Center for the Training and Production of Agamic Seeds (CEBISA) | It is a local germplasm bank that has adopted conventional genetic improvement processes without resorting to genetic modification through transgenesis. | | – Re-building of the social fabric and rescue of native potato seed.<br>– Production of improvement seeds as "*Angostureña*."<br>– Building of technological appropriation process. |

Elaborated by ourselves. The categories were constructed since theoretical discussion and inspired by the systematization of "Fundação Banco do Brasil-Rede de Tecnologias Sociais.

methodological approach was the Campesino a Campesino movement, an agroecology production strategy rooted in the principles of sustainability and emphasizing the exchange of knowledge and experiences among farmers (Rosset and Val, 2018; Holt-Giménez, 2008). The main achievement was collective work and the design of an organizational route to manage the reconstruction of the seedbed social fabric in Gavidia. It was possible because of strategies such as participation and knowledge co-construction.

The centrality of the encounter between different epistemic paradigms to make the project viable points to the connections between the concept of intercultural translation and the innovative use of social technologies in border contexts. As we have seen, the border is an interstitial space for negotiating differences, from which new narratives are produced. According to Friedman (2001), in multicultural environments, the mosaic metaphor silences how difference is configured and reconfigured through continuous interaction. For this reason, she proposes the metaphor of twilight to characterize intercultural encounters. In other words, she describes the intermediary space as a place of constant migration and permanent back-and-forth movement. This twilight zone, which is constantly negotiating its position, is conducive to innovation. The translatory rationality that emerges from the border is cosmopolitan and open to articulation. The intelligibility between practices and knowledge that meet, clash, and interact allows ethical and political convergence (Ribeiro, 2005). Regarding social technologies implemented in contexts of cultural plurality, the concept of border space - or twilight, according to Friedman - is relevant because it breaks down epistemic hierarchies and proposes a real complementarity between different types of knowledge.

An outcome of the project that exemplifies the emergence of border spaces in that context was the creation of the *EcoFestival* of the Native Potato of Venezuela. This event aims to bring together seed guardians, share the progress of the rescue efforts, provide training to farmers, and help rebuild Gavidia's social and agroecological framework. The first *EcoFestival* was held in 2012 with various actors and institutions. The seventh festival in 2019 took on an itinerant format, visiting different locations in the *Páramo* and incorporating wheat as a twinned crop to the potato system. This festival was part of a broader project financed by the Small Grants Program of the Global Environment Facility - GEF-SGP (Global Environment Facility, 2024).

The 12th *Ecofestival* was celebrated in 2023. The Ministry of Science and Technology (MINCYT-Spanish acronym) and the Corporation for Scientific and Technological Development (Codecyt S.A.), a state-owned company attached to the Ministry, supported the event. The *Ecofestival* is a highlight because of its claims and its embodiment of a set of local practices and knowledge for solving local problems, but not only. The *Ecofestival* prioritizes social well-being and community empowerment, addressing issues such as environmental degradation, genetic erosion, and inequality.

Celebrations are more than the product of the practical conditions and purposes of collective work and go beyond the biological need for periodic rest (Bakhtin, 1987). According to Guarinello:

> [A feast] is always a production of everyday life, a collective action that takes place in a defined and special time and place, involving the concentration of affections and emotions around an object that is celebrated and commemorated and whose main product is the symbolization of the unity of the participants in the sphere of a particular identity. A feast is a point of confluence of social actions whose purpose is the active gathering of the participants (Guarinello, 2001: 972 [free translation]).

This definition of a festival is linked to a non-crystallized understanding of culture and identity, which are forces that move and articulate in the arena of power relations (Hall, 1996). Considering that the *Ecofestival* involves actors from various epistemic universes, it can be understood as a space for community empowerment and identity strengthening. It also offers an opportunity for convergence around potato rescue strategies, constituting a border space conducive to translatory processes.

## 3.2 Biotechnology center to produce agamic seeds – CEBISA: biotechnology "managed by people from the same field"

The Biotechnology Center for the Training and Production of Agamic Seeds (CEBISA-Spanish acronym) is a germplasm bank belonging to the Association Integrated Producers of the Páramo (Proinpa). Proinpa was born from the agreement of different perspectives on páramo agroecological management. On the one hand, the Tropical Andes Program (PAT-Spanish acronym) and, on the other, the interests of a heterogeneous group of farmers are differentiated by land ownership and their level of education, from incomplete high school to postgraduate.

PAT arrived in the páramo in 1996 to provide technical and social assistance to the region's communities, especially on topics such as tourism and sustainable agriculture. The program was part of a broader international cooperation project funded by international and national institutions. Some authors (Llambí, 2012; Richer, 2005) emphasize that PAT introduced agroecology as a reference for a new ecologically sustainable agricultural production pattern, more aligned with local cultures. Nevertheless, when PAT arrived in the Mérida Páramo mountains, Venezuela already had established expertise in ecological and environmental agricultural sciences (Velázquez, 2003; Hofstede et al., 2014), and discussions about conservation and agricultural production had already taken place.

Additionally, some of the founding members of Proinpa also participated in socio-organizational and agroecological activities in the páramo during the same period. Some of the founding members of Proinpa, small farmers with extensive experience or belonging to socio-economically differentiated families with a long farming tradition—owners of plots between 3 and 10 hectares or heirs of family-owned properties—had pursued careers directly related to agricultural activities in the region. Some managed to start technical careers, bachelor's degrees, or engineering in agronomy, agroforestry, and education, among others. In this process, the students/farmers showed their ability to translate different cultural and epistemic perspectives, acting as key players within the border space.

Upon obtaining the bachelor's degree and returning to the páramo, the farmers, along with PAT, recognized agroecology as one of the best responses to some socio-environmental conflicts in the region, like the expansion of the agricultural frontier (Romero and Romero, 2007). The proposal emerged to create an official public training program through a system of technical high schools focused on adult education to primarily address the environmental and

agroecological demands of the páramo. A technical degree in agroecology was created within the same municipality linked to the Nestor Contreras Toro High School, an institution oriented to educating young people and adults. Some conflicts arose in obtaining a working space, as well as the necessary agreements and permission from the Ministry of Education and the Ministry of Agriculture, among others. Finally, they succeeded in formalizing the technical grade in agroecology, and 150 graduates were trained.

After 4 years of collaboration with the Páramo producers, PAT ended the experimental project because of funding cuts from development agencies in 2002, and "the 25 producers who took part in the experimental project chose to establish a productive organization, which later became the Association of Integrated Producers of the Páramo (Proinpa)" (Llambí and Duarte, 2005).

We call the process of forming Proinpa the *founding stage*. This moment allowed the foundations of CEBISA to be laid. It began with the PAT partnership and continued until the formalization of the organization in 2002. Thenceforth, Proinpa achieved approval for small projects to produce locally improved seeds. In 2003, MINCYT funded the construction of a 500 $m^2$ greenhouse. It is situated in a cultivated Páramo area at 3,400 m above sea level in the *Sierra de la Culata*, specifically in the *'La Angostura'* sector of the Rangel Municipality (Romero, 2005). The funds were allocated by the Productive Innovation Networks (RIP). Initially, the project was experimental, with the goal of producing certified potato seeds under agroecological conditions adapted to the local ecosystems' biophysical conditions.

Additionally, it aimed to reduce the seed importation process (Llambí, 2012, p. 22). However, they soon began to have problems with the supply of seedlings, which led them to embark on a new project: the construction of a potato seed laboratory. Following the development of a project supported through partnerships with universities and agricultural researchers, Proinpa established a Biological Supplies Laboratory within a 40-square-meter classroom at Nestor Contreras Toro High School. Some graduates in the technical grade in agroecology started working in the laboratory, most of whom were women.

The Proinpa associates continued developing projects to build their own laboratory, and they were funded by an entity attached to the MINCYT. In 2015, CEBISA started operating in 167 square meters (167 $m^2$) next to the greenhouse. CODECYT has played a crucial role in advancing the projects and objectives of the RIP-SP and PROINPA. This support has included financial backing, technical assistance, and close guidance in operational management. The center has an annual production capacity of 250,000 plants, potentially supplying 3,000 $m^2$ of greenhouse space and producing 5,000 tons of registered seed. This would substitute 50% of the national imports of this resource Patiño Villafañe (2015).

From the perspective of seed production techniques, CEBISA employs agamic propagation, also known as asexual propagation or plant cloning. Among its innovations, the "Angostureña" stands out as a new and highly relevant genetic material. According to an internal report from PROINPA, this clone demonstrated exceptional performance during various evaluations, with yields surpassing 45 tons per hectare. It also exhibited remarkable adaptability to medium and high altitudes (1,800–3,500 meters above sea level) within the potato-growing regions of the Venezuelan Andes. Additionally, the "Angostureña" achieved a 78% reduction in the use of chemical products for controlling *Phytophthora infestans*, a significant pest in potato cultivation.

This process is closely tied to biotechnological expertise that goes beyond the techniques typically employed by local or family farmers. CEBISA does not intend to employ other techniques, such as transgenesis, in the foreseeable future. It maintains an active stance in defending anti-transgenesis practices in food resources and promoting the free circulation of seeds.

## 4 Discussion

The study by Cebisa and NuBaSe in the páramos of Venezuela shows that farmers in the region have developed a close relationship with potato landraces. Whether through the construction of dialogs between conventional technologies and social technologies, such as CEBISA, or through the reconstruction of ancestral social technologies, such as the *Ecofestival*. Although it's still too early to identify a specific seed identity, there is a clear and strong socioeconomic focus on potato seeds. Even though some producers in Gavidia have a close working relationship with Proinpa and even collaborate with them, there are still differences in the production technology and economic organization between these two communities. These distinctions emphasize the position of producers who were later integrated into the commercial potato production system.

The NuBaSe and Cebisa can be considered social technologies because they were created to promote social inclusion, participatory processes, and culturally contextualized practices. These technologies embody principles of accessibility and empowerment (Dagnino, 2009), contributing to sustainable development goals by promoting autonomy and resilience within marginalized communities. They also reinforce the value of indigenous and local knowledge systems (Silva et al., 2020). In contexts such as the páramo of Mérida, a region susceptible to human activities such as industrial and agricultural production, social technologies assist in the conservation of genetic diversity, which, as in the case presented, has allowed the counting of more than 50 species of landrace and improved potatoes (Romero, 2005; González et al., 2016; PROINPA, 2019). On the other hand, the development of a medicinal plant production program under an organic scheme in crop association, using species such as *Allium sativum, Ruda Ruta graveolens, Caléndula, Ajenjo, Ortiga, Clavel de muerto*, among others, has shown positive results for the diversification of production and the rescue of other ancestral knowledge associated with health care (PROINPA, 2019).

We can consider the local potato seed production system in the Mérida *Páramo* as a common resource, in line with Ostrom's (2000) concepts of self-organization and self-management within the communities and local agents that form the system, in contrast to external dynamics trying to be imposed on the system. Similar to other experiences of building social technologies in Latin America, including La Via Campesina and the Landless Rural Workers Movement, the efforts to rescue native seeds and produce local seeds in Venezuela through technological appropriation can contribute to the development of public policies in the region. The example discussed here reflects the relationship between the concepts of social technology and intercultural translation,

pointing to the importance of breaking down epistemic hierarchies to innovate on a multi-epistemic basis. To ensure effective public policy development, especially in contexts of cultural diversity, it is important to prioritize political participation, resource transfer, and culturally appropriate technical assistance following methods adapted to the context.

There is plenty of evidence on the seed recovery process in the páramo de Mérida, mainly in the areas of ecology, agronomy, and economy. In this work, we seek to deepen our understanding of the processes of construction of social technologies undertaken by seed-producing communities to achieve the recovery and custody of native varieties and production in local systems. On the other hand, this study is part of a broader research project on the dynamics of knowledge production, not only among the guardians and producers of potato seeds but also between them and actors from other spheres of knowledge, such as researchers from universities in the region, local and national governments, civil society organizations, research centers, funding agencies, etc. Innovative results have been achieved through ST and the encounter between different epistemologies.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving humans were approved by University of Campinas - Unicamp. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

IL: Writing – original draft, Writing – review & editing. CÁ: Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

## Publisher's note



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# Knowledge management and the power of communication: INDESGUA as a social technology enabling equitable access to scholarships in Guatemala

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This community case study examines the actors, conditions and context in which scholarships offered by international cooperation programs to access higher education are managed in Guatemala. It documents a communication-based social technology initiative led by organized local civil society: the Institute for the Development of Higher Education in Guatemala—INDESGUA, a nonprofit organization founded in 2007. Using a qualitative methodology that combines in-depth and semi-structured interviews with an analysis of organizational records, this article reflects on the mediating role INDESGUA plays between individuals (demand side) seeking scholarships and providers (offer side), with specific objectives of facilitating access to traditionally excluded groups of Guatemalan society, specifically rural youth, young women, and indigenous populations. The analysis covers 2007 to 2023. The findings show that knowledge management and communication are central elements of INDESGUA's operation and promote social inclusion. However, structural inequalities and contextual systematic biases may limit the effectiveness of these efforts.

KEYWORDS

**scholarships, communication, social technology, INDESGUA, Guatemala, higher education, international development cooperation, knowledge management**

## 1 Introduction

Guatemala, classified as an upper-middle-income country (World Bank, 2023a), is located in Central America. Despite having the largest economy in the sub-region, it faces alarming levels of poverty and inequality. The nation is characterized by a small and ineffective state with chronic deficiencies in providing basic public services. Long-standing shortcomings in infrastructure and education, persistent social conflict, and poor governance (International Monetary Fund, 2023; Organization for Economic Co-operation and Development et al., 2023) exist at the expense of its population of nearly 18 million people. Over 50% of the population lives in poverty, with indigenous and rural communities disproportionately affected (Velásquez, 2022). Inequality and exclusion also partially explain low Human Development Indicators (HDI). The latest figure (United Nations Development Programme, 2024) ranked Guatemala 136th out of 190 nations, placing it among the lowest in Latin America. Guatemala has a fragile education system, which shows indicators of insufficient coverage, low quality, and

several geographical and social inclusion gaps at various levels, including primary, secondary, and higher education (World Bank, 2023b; Asociación de Investigación y Estudios Sociales, 2017). The average years of schooling in Guatemala is only 5.7, compared to 8.7 in the broader Latin American region. Although public coverage in primary education is relatively adequate, secondary, and higher education suffers from low coverage and quality (World Bank, 2023a,b; Asociación de Investigación y Estudios Sociales, 2017). Educational outcomes in Guatemala are significantly lower than those of neighboring countries. In 2022, public expenditure on education was only 3% of GDP, less than half the Latin American regional average (UNESCO Institute for Statistics, 2024). The situation is similarly worrisome in higher education. According to the Instituto Nacional de Estadística (2020), in 2023, there were 519,561 students enrolled at the tertiary level (including technical, undergraduate, and postgraduate), while 41,529 people obtained a tertiary-level degree. This figure is consistent with estimations that only 2.6% of the population has access to higher education in Guatemala (UNESCO-IESALC, 2018). In higher education, structural inequalities have created sustained and varied gaps between rural and urban settings, resulting in exclusionary practices that limitaccess to education for various population sectors, mainly young women, indigenous and afro-descendant youth, and rural communities (United Nations Educational, 2020). Guatemala lacks institutional structures, public policies, and instruments with a specific mandate to promote inclusion schemes in the Guatemalan higher education system. Consequently, a markedly higher degree of inequality can be observed in tertiary education (Bashir and Luque, 2012). With a weak local higher education system, comprised of only one public university and 16 private universities (Consejo de la Enseñanza Privada Superior, 2024), Guatemalans have sought for decades to obtain funding and support—mainly scholarships, but also loans, fee waivers, partial discounts—from international cooperation to access higher education (Bonilla and Kwak, 2014; Bonilla and Kwak, 2015). There is no centralized public system to coordinate, manage and implement the effective use of scholarships, since only the General Secretariat for Planning and Programming of the Presidency (SEGEPLAN) has the mandate to "create and manage a bank of scholarships provided by the international community (Congreso de la República, 1997: art 14, j). The coverage, actions, and performance of SEGEPLAN in this mandate have been assessed as limited and restricted by Woo and Reyes (2018) due to the insufficient infrastructure, personnel and basic intermediary role played by the institution (Morjan De La Vega, 2019). The concentration of SEGEPLAN's activities in the capital city of Guatemala has also reduced access for scholarship seekers based in rural communities. The Institute for the Development of Higher Education in Guatemala (INDESGUA) was founded in 2007 as a communication-based social technology rooted in civil society. This community case study explores the actors, conditions, and context in which educational opportunities are managed in Guatemala. It also documents INDESGUA's role in mediating between individuals seeking scholarships (demand side) and scholarship providers (offer side), with a focus on facilitating access for traditionally excluded groups in Guatemalan society.

## 2 A brief account of relevant literature on scholarship programs for access to higher education

According to Kent (2018), scholarship programs are typically structured based on geographic focus, levels, or fields of study, and can significantly impact access to education for specific population groups. In developing countries like Guatemala, these programs often serve as mechanisms to challenge the social and political structures that perpetuate educational inequalities. Consequently, access to higher education through scholarship programs can enable beneficiaries to become agents of social change within their communities and countries (Dassin and Navarrete, 2018). In this regard, Kent identifies key trends in international scholarship programs, including government-sponsored initiatives implemented by developed, developing, or middle-income countries through their educational entities (Ministries of Education or universities); multilateral agencies (World Bank, Asian Development Bank); private foundations (e.g., Open Society Foundations, Ford Foundation, and Mastercard Foundation); and other organizations dedicated to developing scholarship programs that aim to expand access to higher education for both national and international students (Kent, 2018).

From the Latin American perspective, Brunner (2013) observes that access to higher education in Latin America is shaped by the dynamics of private financing, as well as mixed or state-subsidized higher education models. This is particularly evident in countries where institutional policies emphasize the role of education investment in driving economic growth and enhancing national human capital. However, significant disparities persist across Latin American countries in terms of higher education access and addressing systemic needs. Considering these challenges, Martel and Talha-Jebril (2021) highlight the critical role of foundations and other nonprofit organizations in ensuring access to higher education through scholarship programs for traditionally excluded groups. These groups include women (particularly rural and indigenous women), people with disabilities, and other ethnic and social minorities. They emphasize the importance of civil society organizations at the local level in establishing connections between communities, programs, foundations, and other key stakeholders to facilitate access to scholarships and uphold the right to education in contexts where exclusion is the norm. From this perspective, the consulted literature identifies examples of foundations that promote access to international scholarships for developing countries, such as the Ford Foundation International Fellowships Program (IFP) and the Mastercard Foundation Scholars Program, among others (Brogden, 2018; Cosentino et al., 2019; Martel and Talha-Jebril, 2021; Rana et al., 2021). The analysis of these initiatives underscores the transformative potential of scholarship programs in reducing educational disparities and fostering social equity. By leveraging the resources and networks of diverse stakeholders, including governments, private foundations, and civil society organizations, these programs can bridge the gap for underrepresented groups. This approach not only enhances individual opportunities but also strengthens communities by nurturing leaders who contribute to broader social and economic development. Expanding and replicating these practices in other regions could be pivotal in addressing global inequalities in higher education access. Therefore, scholarship programs are vital instruments for addressing unequal access to higher education in developing countries. Different

actors, through diverse initiatives, have contributed not only to counteracting these asymmetries, but also to fostering social development by implementing innovative strategies, such as social technologies: connecting students and young professionals from underrepresented populations to educational opportunities through communication, knowledge, and information management. These approaches not only enhance individual prospects but also empower communities by cultivating leaders capable of driving sustainable development and systemic change. It is important to mention that the general objective of international cooperation is to mitigate the major global challenges established in the Sustainable Development Goals (SDG). In the specific case of scholarships, the main purpose is to promote the development of developing countries through the formation of human capital, with the expectation that beneficiaries will return to their countries to contribute to the progress and well-being of their communities.

Finally, in the case of Guatemala, there is limited literature on the provision and administration of scholarships. Bonilla and Kwak (2015) examined the role of postgraduate scholarships as a mechanism through which donor countries have collaborated with Guatemala to develop national capacities. Their study provides evidence that donor support has indeed contributed to the development of capacity in Guatemala; however, the absence of public policies for human resource management, the dynamics of the international cooperation process, and particular features of the domestic context hinder the effectiveness of the international cooperation scheme, thereby limiting its outcomes and impact.

## 3 Detail to understand key programmatic elements of the community case

This community case study employed a qualitative methodology. Primary data were collected from three groups of participants with rich knowledge, involvement and understanding of the establishment and operation of INDESGUA (key respondents): (i) Members and former members of the Directive Board of INDESGUA; (ii) Group of collaborators with different levels of involvement in volunteer services provided in the operation of INDESGUA; (Table 1) and (iii) Representatives of selected organizations/institutions mediated by the actions/services provided by INDESGUA. In this group, individuals from universities, public institutions, organized civil society (both local and internationally) were included. Figure 1 details the composition of this group. For selecting the first and second groups, criteria were designed to guarantee a diversity of views and perspectives including gender representation and knowledge/involvement during different stages of INDESGUAS's trajectory. Additionally, the registry of 1,658 successful applications (formative opportunities obtained) was analyzed (see Tables 2, 3).

Participants from groups (i), (ii), and (iii) participated in semi-structured interviews. Additionally, INDESGUA provided an anonymized database of scholarships awarded between 2007 and 2023, based on self-reported information from scholarship seekers.

To achieve the general objective of this study, a literature review and desk research were carried out in addition to collection of primary data. All interviews were recorded using various digital platforms and software (e.g., Google Meets, Zoom, and WhatsApp). The semi-structured interviews lasted 45 min on average. A total of 30 h of audiovisual material was recorded. All materials were codified and analyzed to determine patterns, trends, common content, and contrasting views.

The Ethics Committee of the University of Technology of El Salvador (UTEC) reviewed the research protocol, design, instruments, and methodological approach for this study. All participants were explicitly informed of their voluntary participation and the possibility of withdrawing from the process at any time, for which they provided an informed consent form prior to their participation. The identities of the participants are not identifiable nor traceable, except for INDESGUA General Director Mr. Luis Edgar Arenas, who provided written authorization to disclose his identity, given the public nature of his role. All interview transcripts were encoded, and the recorded material was accessible only to the research team.

## 4 Context in which INDESGUA was founded

Ethnic and racial inequalities are fundamental drivers of social inequality in Latin America and the Caribbean, with racism sustaining a self-perpetuating culture of privilege (UNESCO; 2022 and 2020). In Latin America, only a few countries report having an indigenous population of more than 10% of their inhabitants, such as the Plurinational State of Bolivia (48%), Guatemala (45%), Mexico (21.5%) and Peru (12.5%). Historically, indigenous groups have faced systemic exclusion, which has disproportionately disadvantaged indigenous students compared to their non-indigenous peers at all levels of education (Velásquez, 2022). The gaps that affect indigenous groups in terms of access to education are more severe than those affecting Afro-descendants, with the deepest inequalities affecting rural areas and indigenous women and men (Corbeta et al., 2018). In Guatemala, access to education is marked by inequality and exclusion at all levels. This is also evident in higher education (Bashir and Luque, 2012). The gender gap in education has somewhat closed in the last few years at lower levels of education, however, there remain disparities in terms of region and ethnicity. Mestizo (and white) students had the highest enrollment rates; boys generally had slightly higher enrollment than girls across all ethnicities. Geographical differences are also significant, with provinces such as Alta Verapaz lagging in coverage while others, like Huehuetenango, showed lower enrollment levels. The Maya population, especially in rural areas, face more significant challenges in accessing education (OES Observatorio de Educación Superior, 2024). In Latin America, the wealthiest 20% are five times as likely as the poorest 20% to do so. In Guatemala, 5% of the poorest complete secondary school, compared with 74% of the richest (United Nations Educational, 2020). Attendance was lower by 3 to 20 percentage points among 15-to 17-year-old indigenous language speakers in the Plurinational State of Bolivia, Guatemala, Mexico, and Peru than among all those identifying as indigenous. One major barrier to attendance is the dangerous journey to school; in Guatemala, many roads are unsafe for girls, and transportation, when available, is often prohibitively expensive.

According to the Guatemalan population projections (Instituto Nacional de Estadística, 2020), the estimated school enrollment rates by

TABLE 1 Coded/participating key respondents through semi-structured interviews.

| M/W | Code | Date of interview | Role–former role in INDESGUA |
|---|---|---|---|
| W | DBM-1 | 2024.06.03 | President of the directive board |
| M | DBM-2 | 2024.01.15 | Vice president and executive director |
| W | DBM-3 | 2024.16.14 | Member of the directive board/graphic designer |
| M | DBM4 | 2024.06.03 | Treasurer and member of the directive board |
| M | DBM5 | 2024.06.27 | Member of the directive board |
| M | GVC1 | 2024.06.20 | Collaborator-website communication adviser |
| W | GVC2 | 2024.06.19 | Collaborator /communication material |
| M | GVC3 | 2024.06.19 | Collaborator—website design and content |
| W | GVC4 | 2024.05.27 | Collaborator-essay reviewing—structuring applications, coaching, counseling |
| M | GVC5 | 2024.08.17 | Collaborator—advising early applicants, drafting study plans |
| W | GVC6 | 2024.06.15 | Collaborator—referring applicants from rural communities in southern and western provinces of Guatemala |
| M | GVC7 | 2024.07.06 | Collaborator—advising applicants in Taiwan, Australia |
| W | GVC8 | 2024.05.31 | Collaborator—advising applicants to local programs in Guatemala |
| M | GVC9 | 2024.05.17 | Collaborator—advising applicants to Fulbright and USA programs |
| W | GVC10 | 2024.07.04 | Collaborator—design and communication materials |
| M | GVC11 | 2024.06.08 | Collaborator—advising applicants in Korea, replying to emails |
| W | GVC12 | 2024.06.21 | Collaborator—referring applicants from rural communities, advising applicants Chile |
| M | GVC13 | 2024.05.20 | Collaborator—advising applicants in Korea, Fulbright, Asia, Europe, reviewing essays |
| W | GVC14 | 2024.08.07 | Collaborator—advising applicants in Belgium—copy-editing communicational materials |
| W | GVC15 | 2024.08.14 | Collaborator—referrals in rural communities in Sololá—advising young indigenous women applicants |
| M | GVC16 | 2024.07.08 | Collaborator—advising applicants in Brazil, Spain, Chile—issuing reference letters |
| W | GVC17 | 2024.07.14 | Collaborator—advising applicants in Mexico, counseling, and coaching |

*n* = 22/5 MDB = member/former member of INDESGUA directive board—17 GVC = group of volunteer collaborators—women: 11 and men: 11.

ethnic group reveal significant disparities. Mestizos[1] show a high enrollment rate of 93%, followed by Mayas at 67%, Garifuna at 16%, and Xincas at less than 1%. These disparities become even more apparent when compared to the projected ethnic composition of the population in 2022: Mestizos (56.01%), Mayas (41.66%), Garífunas (0.13%), Xincas (1.77%), and Others (0.43%). This comparison underscores substantial inequalities in educational access across ethnic groups. There are also disparities in school enrollment regionally. For instance, Alta Verapaz, Chiquimula, and Petén were the leading departments, with coverage rates exceeding 85%. This means that at least 85% of the population aged 4 to 18 was enrolled in school in these regions. On the other hand, Chimaltenango and Huehuetenango had the lowest coverage rates, both at 71%, despite Huehuetenango being the third department in terms of total enrolled students at the national level.

## 5 Findings and discussion

Enhancing access to higher and technical education is essential for the development of Guatemala. National and international universities, along with technical institutes, offer a broad range of educational opportunities. However, access to them is only possible for a small portion of the Guatemalan population. There are several factors that hinder this, including:

- The persistence of the social, political, economic, and cultural exclusion patterns of the national development model.
- Economic constraints affecting large sectors of the population.
- The deficiencies in coverage and quality of public and private education at the primary and secondary levels.
- Weak institutional guidance systems that provide limited information on career paths, entry requirements, retention, and opportunities for scholarships or other financial aid.

For these reasons, INDESGUA emerged as an initiative created by a group of professionals aimed at contributing to build human capacities in Guatemala (Arenas, 2024). These professionals recognize that access to educational processes is a citizen's right. This group has, in recent years, carried out systematic actions of support, advice, and accompaniment to facilitate students' access to higher and technical education processes both in Guatemala and abroad. Based on this experience, this group has strengthened its conviction that it is possible to contribute to the development of the country through an increasing participation of all people; men and women; young people and adults; Mayans, Afro-descendants, Xincas and Ladinos or mestizos, in higher and technical education processes.

1 Mestizo is a term in Spanish that means "mixed race," used in Guatemala to describe people of mixed ancestry with a white European and an indigenous background.

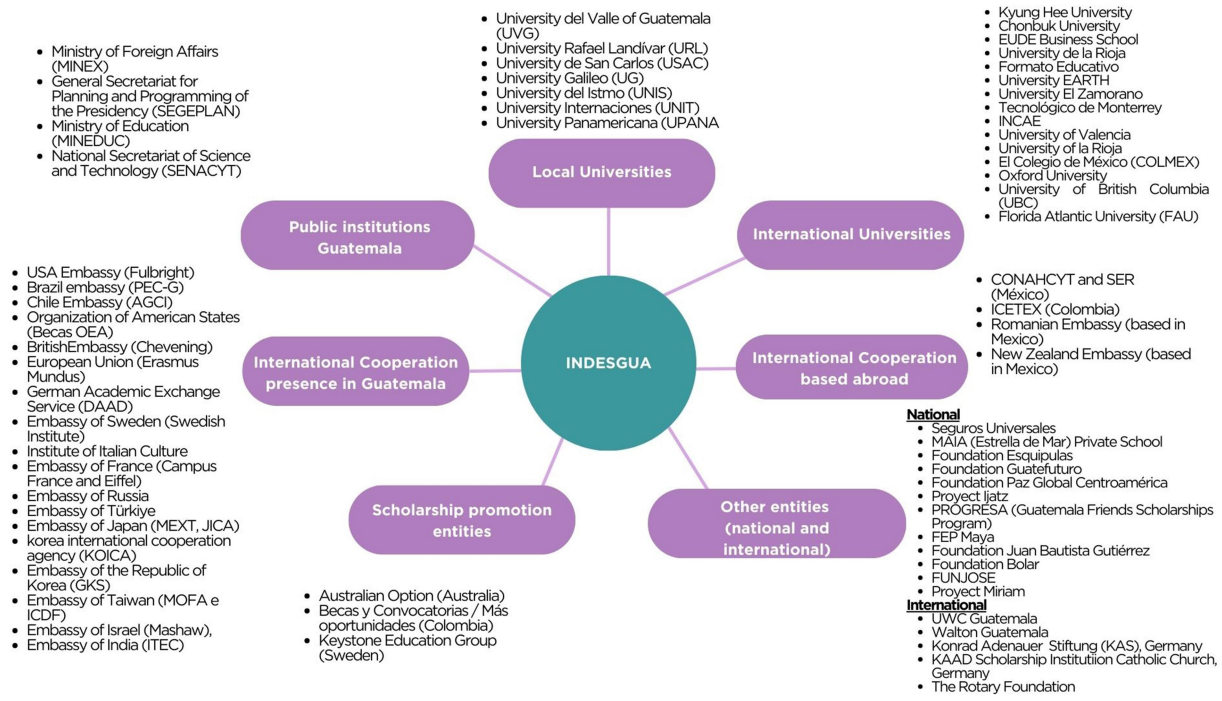


FIGURE 1
INDESGUA—engagement with institutions/organizations/entities.

## 5.1 Foundation and evolution of INDESGUA

INDESGUA is a Guatemalan Civil Association and not-for-profit organization, officially created and registered on June 26, 2007 (Calderon de Leon, 2007). Initially formed by a small group of research-oriented professionals, it has evolved to systematically incorporate volunteer efforts. INDESGUA has its own legal representation and assets. Its main purpose is to advise students and professionals of Guatemalan nationality on the management of scholarships, loans, and educational aid to continue higher degree studies and postgraduate studies in Guatemala or abroad. The mission adopted by INDESGUA is to contribute to the inclusive and sustainable development of Guatemala, through the academic and professional training of its inhabitants, in higher education supported by scholarships and other mechanisms. The Vision followed by INDESGUA, according to its constitutive documentation (Calderon de Leon, 2007) is to become a leader in scholarship promotion and calls for applications in Guatemala. INDESGUA defines its work as promoting equal opportunities and non-discrimination regardless of ethnic condition, religious or political affiliation, gender, age, sexual orientation, ability, nationality, place of residence, or economic possibilities. Its values are cited as: commitment; honesty; determination; gratitude; solidarity; simplicity and innovation.

## 5.2 INDESGUA governance and operations of INDESGUA

Since its creation in 2007, INDESGUA has consistently promoted admission processes and scholarship opportunities so that young Guatemalans can have timely information to access scholarships and financial aid that facilitate higher education at different levels (technical, bachelor's, master's, postgraduate and specialized short courses).

Figure 2 illustrates the governance and operational scheme of INDESGUA. The Directive Board, represented in purple, serves as the organization's main decision-making body, responsible for legal representation, calling meetings, and managing tasks such as registration with authorities and tax declarations. The General Director, illustrated in black and white, is placed in a central position. He is also a member of the Directive Board (purple) and plays a pivotal role in coordinating activities and delegating tasks to the group of volunteer contributors. The pivotal role of the General Director is exemplified by Mr. Luis Edgar Arenas, who has held this position since INDESGUA's creation in 2007. He has served as the backbone of the organization, facilitating the functions and operations of the governance structure. However, his central role also presents a challenge for replicating the model in other contexts, given the time-consuming and demanding nature of the position. The group of volunteer contributors carry out different tasks including website design, social media management, video editing, and audiovisual content creation while replying to emails, sharing stories, counseling, and assisting applicants. The next element of the figure incorporates individual applicants or scholarship seekers, those actively involved in the application process, seeking help to secure opportunities. They are committed to their process, or rather processes; in most cases, each applicant engages in more than one scholarship application process. At the right end of the figure, the potential beneficiaries and broader sectors of society are represented in light blue. Most frequently,

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TABLE 2 Trajectory—knowledge management and communication engagement over time INDESGUA 2007–2023.

| Analytical categories | 2007–2011 First period, producing early knowledge products, setting bases for systematic unidirectional communication | 2012–2019 Second period, enhancing knowledge products, introducing comprehensive bidirectional communication systems | 2020–2023 Third period, producing sophisticated knowledge products, applying multidirectional communication systems |
|---|---|---|---|
| Knowledge management | - Gathering and collecting scattered information about scholarships<br>- Mapping, introducing schematic approaches to information<br>- Applying first filters, organizing relevant data (by destination, by level of education, by target group)<br>- First scholarship guides with general advice on applying to different scholarship programs. | - Direct collaboration with scholarship providers was intensified, resulting in wider and more systematic access to calls for applications that, without the role of INDESGUA, would be not accessible to Guatemalan society.<br>- - Production of an informational monthly scholarship newsletter<br>- Personalized counseling, tailoring information to smaller groups of applicants or individual scholarship seekers | - Shift from informational guides to specialized scholarship catalogs<br>- Enhancing coverage to information for online trainings and remote education, i.e., E4CC training for English language skills, Formato Educativo and online MBA, University of la Rioja<br>- Categorization of scholarship opportunities by level of education, by source of funding, by geographic destination |
| Communication engagement | - Used Yahoo email account with limited reach to share information<br>- Publication of Scholarship Newsletter, 10,000 subscribers<br>- National tours with high school students in rural territories<br>- Enabling Subscription to periodically receive newsletters<br>- Informational website (only organizational information)<br>- Social media incursion: creation of a Facebook page.<br>- Producing and sharing material: "Fulfilling goals and making dreams come true," in which scholarship awardees share their experiences | - Specialized workshops and personalized assistance to prospective scholarships beneficiaries<br>- New design of INDESGUA's web portal and Scholarships-Newsletter enhancement, 50,000 subscribers<br>- Expansion of other social media platforms: Twitter, Instagram, YouTube<br>- Systematic participation in scholarship fairs, conferences, and other activities, mainly in universities, but also public institutions (SEGEPLAN, SENACYT), and civil society organizations (Seguros Universales) | - The pandemic impacted communication engagement, resulting in a predominance of online workshops with scholarship seekers.<br>- Broadening the reach beyond Guatemalan applicants towards other nationalities, mostly in Latin America<br>- Intensifying engagement with media and press |
| Offer side scholarship programs setting trends | - Predominance of the Classic Model: international scholarship programs were mostly managed by SEGEPLAN, therefore, in the offer side, emphasis was placed on international cooperation towards national development, i.e., Scholarships for Bachelor in Medicine (ELAM-Cuba; Walton foundation), Master (Ford Foundation) and Technical Level (Semilla—Seed Scholarships), INDESGUA's actions reflected this offer-National scholarships targeted undergraduate and postgraduate programs with clear priority on rural youth: e.g., Ijaz Project, FEP Maya, PROGRESA | - Expansion to the Modified Classic Model in which a letter of admission from a program included in the academic offer of the scholarship program is required. AGCID-Chile, ICDF-Taiwan; SRE-Mexico, DAAD Regional, Scholarship programs from Colombia, Argentina, Brazil<br>- Due to the evolution of the models, several embassies/cooperation agencies reduced staff in Guatemala<br>- that were specifically assigned to managing scholarship programs. | - Evolution to the Modern Model: in which scholarships are managed in direct contact with universities—several European Union funded-programs like<br>- CONACYT Mexico and Eiffel Scholarships from France<br>- MBA programs with Formato Educativo<br>- Calls for scholarship are mostly<br>- shared by partner countries/ organizations on their websites, with no direct contact with scholarship seekers |
| Demand side common features of scholarship seekers | - -A greater number of applicants for undergraduate university scholarships (university technical and bachelor's degrees) were supported compared to postgraduate scholarships (master's and doctorate degrees)<br>- Among the Guatemalans who obtained scholarships, there were more people from the provinces and rural areas than from the capital: Guatemala City.<br>- The highest percentages of indigenous/Afro-descendant scholarship recipients were achieved (compared to the other periods),<br>- Although there was a slightly higher percentage of women, gender equity was observed among the scholarship recipients. | - More students and professionals from urban areas applying to programs: undergraduate and graduate studies.<br>- Outreach expansion: students and professionals from other countries in Latin America access information to scholarship opportunities through INDESGUA.<br>- Applicants from other nationalities in Latin America, especially Central America, require services and support from INDESGUA. | - Due to the continuous expansion of the scholarship offer, the demand also expanded.<br>- Several programs targeting a particular group, i.e., public officers, organized civil society, became more flexible to include other sectors.<br>- In this period more individuals applied to scholarship programs with less specifications. In other words, academic excellence became more prevalent than potential impact in the country's development. |

TABLE 3 INDESGUA—results overview-accessed formative opportunities 2007–2023.

| | No. scholarship awardees | % |
|---|---|---|
| **Training/education destination** | | |
| Training/education overseas | 901 | 54.34 |
| Training/education in guatemala | 538 | 32.45 |
| Online—remote training/education | 219 | 13.21 |
| **Total** | **1,658** | **100.00** |
| **Nationality** | | |
| Guatemala | 1,557 | 93.91 |
| Other nationalities | 101 | 6.09 |
| Total | **1,658** | 100.00 |
| **Gender** | | |
| Men | 674 | 40.65 |
| Women | 984 | 59.35 |
| Total | **1,658** | 100.00 |
| **Ethnic group** | | |
| Mestizo | 1,375 | 82.93 |
| Maya | 265 | 15.98 |
| Afro descendant | 10 | 0.60 |
| Asian descendant | 8 | 0.48 |
| **Total** | **1,658** | **100.00** |
| **Level of education/training** | | |
| Secondary education | 26 | 1.57 |
| Technical degree | 24 | 1.45 |
| Languages | 292 | 17.61 |
| Short courses/specializations | 251 | 15.14 |
| Undergraduate studies | 257 | 15.50 |
| Master degree | 780 | 47.04 |
| Doctoral degree | 28 | 1.69 |
| **Total** | **1,658** | **100.00** |

potential beneficiaries are high-school and university students who engage with the organization through email or social media. As the communication products created by INDESGUA to promote access to scholarships are open to the public and free of charge, anyone interested can participate in the scheme. Finally, parents or guardians of applicants who are minors occasionally communicate with the organization, supporting young applicants and reviewing the provided material. INDESGUA has, since its foundation, grown in its direct interactions with different stakeholders at the institutional and organizational level. Figure 1 illustrates the relationship that INDESGUA has developed over the years with different local and international universities. A critical part of INDESGUA's operation is also determined by trends on the cooperation side, including interactions with representation in Guatemala, as well as regional and international operations. In addition, frequent interactions and exchanges take place between INDESGUA and four public institutions: The General Secretariat of Programming and Planning of the Presidency (SEGEPLAN), the Ministry of Foreign Affairs (MINEX), The Ministry of Education (MINEDUC) and the National Secretariat of Science and Technology (SENACYT).

## 5.3 INDESGUA trajectory and function as a social communication technology enabling inclusive access to scholarships

INDESGUA was certified as a social technology through a competitive process implemented by the Banco do Brasil Foundation (2019). This acknowledged INDESGUA as a "replicable" initiative, involving techniques and methodologies, developed in interaction with the community and which represents effective solutions for social transformation" (Banco do Brasil Foundation, 2017:3). To be certified, the initiative must meet the following criteria: It must have been implemented, be active and have proven results of social transformation; it must be systematized in a way that allows the reapplication of the technology by other communities. The local community must have taken part in the development, implementation, or reapplication of the Social Technology. The initiative must also include the following dimensions: Social protagonism, cultural respect, environmental care, and economic solidarity. Through knowledge management and communicational engagement, the criteria listed above are salient features of INDESGUA's engagement in its community. As suggested by Morjan de la Vega (2019), while other organizations implement information sharing as a one-way process, INDESGUA's approach is documented as bilateral and multilateral, communicating with individuals, entering dialogues — whether face-to-face, by email or other means. Communication is about asking questions and listening to answers. It is about receiving information, analyzing responses, reassessing positions, and moving the discussion forward. Morjan de la Vega (2019) identifies INDESGUA's as a validated model for coaching students into higher education scholarships. Alvarado Fajardo (2018) agrees and calls attention to the importance of INDESGUA's digital graphic material to promote educational opportunities and professional advisory services that it offers to Guatemalan youth on social networks. She said that the design of the digital graphic material on social networks has enhanced the promotion of educational opportunities and professional advisory services that the Institute for the Development of Higher Education in Guatemala-INDESGUA-offers to Guatemalan youth.

Among all the interviewees, there is a consensus on the unique role that INDESGUA plays in Guatemala. INDESGUA's trajectory has allowed it to emerge as a key player facilitating opportunities for higher education and advanced training by providing unique and detailed access to scholarship opportunities. The interviewees stressed that, without the information provided by INDESGUA, several opportunities would have remained out of reach. INDESGUA's role is pivotal in democratizing access to educational opportunities, particularly in a context where information is often scarce due to the intricate nature of the application processes that vary between calls, academic, technical and cooperation areas. Despite financial limitations, INDESGUA has successfully mobilized a dedicated team of volunteers who have contributed to reviewing applications, searching for opportunities, and supporting applicants throughout the process. This support network has been essential for the organization's

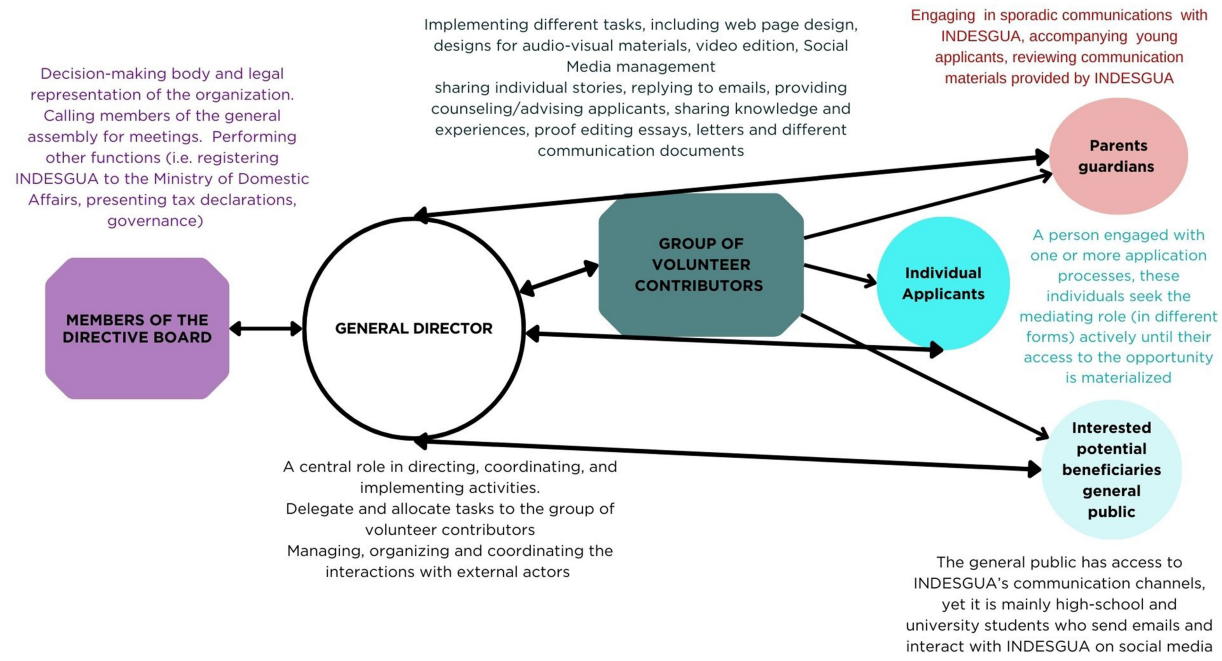


FIGURE 2
INDESGUA—governance and operational scheme.

continued operation, enabling its standout feature—personalized assistance. Volunteers help identify suitable programs, review essays, and guide applicants through the processes. This support has been identified as a critical factor in the success of applications, and the voluntary work has helped mitigate the lack of financial resources.

One of INDESGUA's strengths is its ability to facilitate equitable access to scholarship information. Over the years, INDESGUA has established itself as a reliable and accessible source to be consulted. As its trajectory has advanced, it has adapted to key technological changes in communication, such as the rise of social media and the widespread use of online platforms like Zoom and WhatsApp, enabling better access to scholarship information. The systematic process of organizing, filtering, and structuring the information has produced knowledge products (starting with scholarship guides, evolving into more sophisticated and complex documents such as scholarship catalogs categorized by level of education, destination, type of funding sources) which are readily disseminated and kept up to date. This has provided for access to accurate and detailed data on both national and international scholarships, allowing scholarship seekers from different socio-economic and geographic backgrounds to apply.

Over time, INDESGUA's 16 years of operation have gained the organization legitimacy, recognition, and validation at the national and regional levels. INDESGUA has established itself as a leader in promoting scholarships through personalized advice and support. This service includes essay reviews, guidance in finding suitable academic programs and the scholarship programs that cover them, making it key for many applicants to improve the probabilityof enrollment. INDESGUA's work and reputation have evolved and even expanded beyond Guatemalan borders, with 102 successful scholarships applications for non-Guatemalan applicants.

However, difficulties in reaching the most vulnerable communities are persistent. Although it is recognized that INDESGUA has made significant efforts to reach Mayan, Garifuna, Afro-descendant, Xinca and rural communities, there is still a significant demographic gap in access to information on scholarships available to these populations (the database shows that 65% of the applicants were born in the province of Guatemala). In addition, the people who need scholarships the most are those who tend to have the most difficulty accessing information or meeting the requirements to apply. For instance, the challenges of starting, continuing, and finishing the application process are recurring problems for several applicants. Even though INDESGUA has promoted scholarship opportunities in different ways and spaces, most beneficiaries still have difficulties in applying for scholarships. INDESGUA's database showed that factors such as lengthy administrative procedures, meeting language requirements, associated costs, and the duration of the process make access difficult, especially for people from rural or indigenous communities.

The interviewees mentioned that the application processes are lengthy and costly. Yet, INDESGUA's work in disseminating and sharing self-systematized knowledge products is available free of charge. It must be noted that many people who apply for scholarships face difficulties due to the complexity and cost of the procedures necessary to apply for the scholarships. This includes expenses related to exams such as the TOEFL or IELTS (English), DELF (French), TestDaf (German), among others, and preparatory courses that require time and financial resources to reach the minimum scores required by universities. In addition, there are other mandatory requirements, such as certified translations of diplomas, grades, and letters of recommendation, which further hinder the application process for some. The estimation of minimum preparatory cost is in between 300 to 500 US Dollars, which represents three times the minimum wage in Guatemala.

INDESGUA devotes efforts to the collection and dissemination of information (not managing funding and consequently not granting

scholarships directly) and systematizes information about scholarship opportunities through different knowledge products (guides, catalogues, organized indexes). However, the scope it has reached remains limited because access to information by the communities most in need remains low, as the INDESGUA's database shows. Despite their efforts to reach indigenous and rural communities, a significant gap exists in who can access the scholarships. According to INDESGUA's database, 82.12% of the applicants recognize themselves as *Mestizo* compared to 15.89% who identify themselves as Mayan, and 0.69 and 0.46% of Chinese descendants and Afro-descendants, respectively. The most vulnerable people, who need these opportunities the most, often do not have the resources or information required to apply, perpetuating structural inequalities.

One interviewee mentioned that the lack of strategic alliances, such as with Municipal Development Committees (COMUDES—acronym in Spanish) and Departmental Development Committees (CODEDES—acronym in Spanish), meansthat INDESGUA has not been able to establish partnerships that could expand its reach at the rural level. These partnerships would be critical to disseminating scholarship information in more remote territories and facilitating access to people who most need it. However, the way these committees work does not allow us to assert that they provide viable and effective options in disseminating information due to their systematic corruption. Additionally, interviewees mentioned that INDESGUA's weakness is its dependence on the work carried out by Luis Arenas. This has meant that responsibilities have not been sufficiently delegated, thus creating a more sustainable structure over time. The future of INDESGUA could be compromised when Arenas ceases to lead the organization. INDESGUA needs to address this issue in order to ensure its long-term sustainability. This dependence has also caused a lack of financing. The organization lacks the necessary funds to expand its coverage, improve its services, and ensure long-term sustainability. Although it has tried to raise funds through donations, this strategy has not been enough to cover its operational needs in the short term. These same financial constraints restrict the capacity for growth and long-term sustainability.

## 5.4 Results and outcomes from INDESGUA's operations 2007–2023

INDESGUA's lifespan can be divided into three phases, influenced by scholarship design, and shifting global geopolitical structures. Regardless of their funding source, international scholarships are being shaped and altered by myriad factors, including budget constraints, commodity prices, regulatory and policy changes, political imperatives, conflict and changing power structures including gender norms. The design and infrastructure that support and maintain international scholarships, such as geographic focus areas or levels of study, can significantly impact access and equity in application processes and will affect the outcomes the programs can achieve (Kent, 2018). These changes have led to the discontinuation of some scholarships with programs, specific targeted populations – i. g. indigenous women and rural youth, that were prioritized by some programs and after a period of time discontinued. With changes to the requirements for the scholarships to be awarded (demanding an advanced command of a foreign language, raising the threshold of grades/GPA), sometimes even without prior notice, the general Guatemalan population is often unlikely to be able to meet.

Table two depicts the trajectory of INDESGUA in three time periods with descriptions of four dimensions of its salient features.

The methodology applied by INDESGUA to engage in knowledge management and communication includes:

a Research: systematic searches for information on admission procedures and scholarship management; and structured engagement with universities and cooperating partners to update information on calls for applications.
b Dissemination of information: preparation of guidelines to access scholarships at different educational levels, countries and regions and their publication on the INDESGUA website. Preparation of weekly and special scholarship newsletters to transmit information on open calls, requirements, procedures, calendars, etc., and their dissemination through the INDESGUA Google Group; conducting conferences and participating in scholarship fairs; and systematic incorporation of new members in the INDESGUA Google Group.
c Participation and management in information and knowledge networks.

Some of the knowledge management and communication products elaborated by INDESGUA over the years include:

- Guide to scholarships and financial aid for continuing undergraduate university studies in the United States
- Guide to university scholarships—undergraduate and graduate—in Guatemala
- United States postgraduate scholarship guide
- Guide to university scholarships—undergraduate and graduate—in Asia (focused on Korea, Japan, and Taiwan, although other countries such as China, Singapore, India) are included
- Guide to university scholarships—undergraduate and graduate—in Latin America
- Guide to university scholarships—undergraduate and postgraduate—in Europe
- University scholarship guide—undergraduate and postgraduate—in Oceania (Australia and New Zealand)
- University scholarship guide—undergraduate and graduate—Canada

INDESGUA has changed how it disseminates scholarship information, reaches the targeted population, and gives guidance and application support, which has led to changes in the population benefiting from the services offered by INDESGUA. For example, from 2007 to 2011, a total of 275 scholarship processes were successfully completed, with 98.6% of the beneficiaries being Guatemalan nationals from all twenty-two provinces and 1.4% being foreign nationals from five different countries. Of the Guatemalan recipients, 44.2% were from the province of Guatemala, while the remaining 55.8% were from other regions across the country. The gender distribution showed a slight majority of female recipients (51.1%) compared to males (48.9%). Regarding ethnic composition, 75.5% of recipients identified as mestizo, whereas 24.5% identified as Maya or Afro descendants. Geographically, 33.1% of the scholarships were awarded for studies within Guatemala, 62.6% for studies abroad, and 4.3% for online courses. The types of academic programs varied, with 21.2% in specialized short courses, 1.4% in language courses,

0.4% in secondary-level education, 2.9% in technical university programs, 39.9% at the undergraduate level, 32.7% at the master's level, and 1.4% in doctoral studies.

From 2012 to 2019, 443 scholarship processes were successfully completed, with 95.5% of the recipients being Guatemalan nationals from all 22 provinces, while 4.5% were foreign nationals representing ten different countries. Among the Guatemalan recipients, 56.7% were from the province of Guatemala, with the remaining 43.3% from other regions across the country. The gender distribution indicated a higher proportion of female recipients (61.2%) than males (38.8%). Regarding ethnicity, 82.8% of recipients identified as mestizo, while 17.2% identified as Maya or Afro descendants. Geographically, 19.6% of the scholarships were awarded for studies within Guatemala, 73.1% for study abroad, and 7.2% for online studies. The programs of study were diverse, including 29.1% in specialized short courses, 1.4% in language courses, 2.0% at the secondary level, 2.0% in technical university programs, 17.6% at the undergraduate level, 44.9% in master's degree programs, and 2.9% in doctoral studies.

The period between 2020 and 2023 proved to be the most successful in INDESGUA's history, despite half of this period coinciding with the COVID-19 pandemic. During this time, a total of 940 scholarship processes were successfully completed, with 91.8% of recipients being Guatemalan nationals from all 22 provinces and 8.2% being foreign nationals from 10 different countries. Among Guatemalan recipients, 58.4% were from Guatemala province, while the remaining 41.6% were from other regions. The gender distribution revealed that 60.9% of the recipients were female and 39.1% were male. Regarding ethnicity, 84.9% of recipients identified as mestizo, while 10.1% identified as Maya or Afro descendants. In terms of the geographic location of scholarships, 39.3% were awarded for studies within Guatemala, 43.4% for study abroad, and 18.2% for online studies. The types of studies included 6.9% in specialized short courses, 30.0% in language courses, 1.6% at the secondary level, 0.4% in technical university programs, 7.1% at the undergraduate level, 52.8% in master's degree programs, and 1.2% in doctoral studies.

INDESGUA has made a significant impact on the democratization of access to scholarships, providing crucial information and support to many individuals. However, it faces substantial challenges related to its reliance on a single leader and lack of funding. To improve, INDESGUA must diversify its sources of income, establish strategic alliances with key stakeholders, and create a more sustainable structure that allows for the delegation of responsibilities and ensures continuity. The knowledge produced through the systematization and dissemination of information on scholarships and the accompaniment and advice to almost 1700 successful cases, means that INDESGUA contributes with access to information and to the improvement of application processes both by helping those interested in applying and providing national and international cooperation agents with data to understand the circumstances of the applicants. Contextualizing INDESGUA's work makes it clear that the barriers faced by the most vulnerable populations to accessing scholarships cannot be overcome only by disseminating information. Solutions must also address structural inequalities by prioritizing specific groups that need additional support in the application process. While this is outside the scope of INDESGUA's mandate—whose primary focus is on disseminating scholarship information and supporting applications rather than granting scholarships, it remains an important consideration for future development.

## 6 Scope and limitations

This community case study examines the impact of INDESGUA's efforts in promoting and helping applicants obtain scholarships. The scope of the research is limited to the data provided by INDESGUA and the interviews conducted with participants who were or are directly involved with the work carried out by the institution. Therefore, the analysis is limited to the specifics of the work carried out by INDESGUA and cannot be extrapolated to other local or regional experiences. Additionally, the data reported by INDESGUA is self-reported by individuals who received scholarships during the study period (2007–2023), which may result in underreporting of successful scholarship processes. Further research is necessary to explore other civil society organizations that promote and provide scholarships, to better understand the populations accessing these opportunities and whether there are notable differences among beneficiary groups.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by UTEC University of Technology of El Salvador. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

KB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. NOB: Conceptualization, Investigation, Writing – original draft. MASC: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft.

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## Conflict of interest

Kleinsy Bonilla and Natalia Ortiz have been members of the Directive Board of INDESGUA for different periods. Besides, the three research team members have been users of INDESGUA's services and participated as collaborators in various volunteering activities. Nevertheless, neither has received salaries, been employed, or had contractual relations with the organization. There is no financial, commercial or any source of funding that may involve a conflict of interest that might lead to questions of bias in the research work or the conclusions/implications of this scholarly work. However, the connections with INDESGUA are disclosed as part of the best ethical practice.

The reviewer GM declared a shared affiliation with the author KB to the handling editor at the time of review.

## Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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# Mentoring women in STEM: empowering through social technologies for enhanced inclusivity and professional growth. A case study

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The use of social technologies for on-line training of women in STEM (Science Technology Engineering and Mathematics) areas was explored for empowering women. Here, a case study on the implementation of a mentoring program focused on fostering the professional careers of women from the Juarez Autonomous University of Tabasco (UJAT), at the southeast of Mexico is presented. By means of an international initiative from the British Council, 32 participants were trained as mentors and mentees at UJAT, and further matched to accomplish a 3 months mentoring relationship. Throughout the sessions, the participants' advances in soft skills (assertiveness, networking, leadership, active listening, self-confidence, ability to set SMART objectives, among others) were analyzed, showing how the use of social technologies promoted the professional development of women through empowerment as a strategy for reducing the gender gap in scientific and technological careers in Latin America.

KEYWORDS

**mentoring, STEM, networking, mentees, mentors, social technologies**

## 1 Introduction

Thanks to advances in communication tools, people can now be connected globally, transcending physical and cultural boundaries. Platforms such as Friendster, MySpace, and, eventually, Facebook and Twitter pioneered creating digital spaces for sharing, networking, and collaboration. Under this context, social technologies evolved from static information-sharing systems to dynamic, interactive platforms. The definition of social technologies remains unclear, but we recognize them as the product of years of technological evolution designed to benefit people. Social technologies are "digital technologies used by people to interact socially and together to create, enhance, and exchange content" (Chui et al., 2012). Social technologies reshaped industries, empowered grassroots movements, and redefined how societies interact, paving the way for a more interconnected world, becoming relevant in the last few years mainly because they help to increase women's connection, communication and empowerment (Hagen and Robertson, 2010; Nord et al., 2017; Nord et al., 2016). For instance, online training has opened new opportunities for people to interact, increasing knowledge and sharing information in all fields. Social technologies help support career development networks for women because they increase their ability

to communicate, produce, publish, and share (Jarrahi and Sawyer, 2013). It has been widely accepted that through social technologies, the development of countries could be accelerated, impacting the economy and well-being of citizens (Nord et al., 2016). In a digital era, the simultaneous use of different strategies for improving employee development in companies and organizations provides additional advantages such as better alternatives for training, motivation, and a sense of belonging for the employees.

Science Technology Engineering and Mathematics areas have been traditionally for men all over the world. However, several policies have been established in the last decade to decrease the gender gap in such areas. Women face a significant underrepresentation in STEM careers worldwide, being more noticeable in Latin America (Inés et al., 2023). Several studies revealed that the gender gap is one of the challenges in gender and diversity that organizations are facing and is not being reduced as expected, especially in STEM areas (Beroíza-Valenzuela and Salas-Guzmán, 2024; Meoli et al., 2024; Verdugo-Castro et al., 2023). In this regard, mentoring programs for women represent an excellent strategy to reduce the so-called gender gap (Aufschläger et al., 2023). This gap is driven by cultural, structural, and social barriers that limit their access, development and leadership in these areas (García et al., 2023). It begins with the low access to undergraduate studies in STEM areas, which consequently tends to decrease even more when women join the workforce.

In this regard, academia is not the exception since women on the faculty face several obstacles that limit their professional development, causing dissatisfaction or frustration, which sometimes even leads them to resign due to a lack of growth opportunities (Casad et al., 2020). The impostor syndrome, glass ceiling, and glass cliff are among the most common situations that women need to overcome during their careers, but unfortunately, most of the time, these phenomena make their progress difficult. According to the British Council, reducing the gender gap in Higher Education Institutions is needed to improve the economic development of countries (British Council, 2022).

It is important to mention some statistics related to gender differences in the state. In Mexico, there is a national program called SNII (*Sistema Nacional de Investigadores e Investigadoras*- National System of Researchers) that evaluates the quality and performance of researchers based on their scientific production, academic achievements, science dissemination and internationalization and categorize into four levels: candidate, Level I, Level II, Level III and Emeritus. According to the National Council for Humanities, Science and Technology (CONAHCYT, 2024), there are 302 researchers active in STEM areas recognized in the SNII that are currently ascribed at Tabasco, but only 103 of them are women, representing the 34% of the total number of researchers in STEM.

Tabasco is located southeast of Mexico and possesses abundant natural resources such as water, oil and gas, and a wide agricultural variety. Historically, most of the middle to upper positions in such areas have been dominated by men, and recently, it has been reported that it is the only state of Mexico in which the gender gap in STEM increased in a study from 2012 to 2022 (IMCO, 2023). However, in recent years, Mexican government policies are promoting the inclusion of women in STEM through the launch of specific programs and recognizing successful women who have entered in these fields (Gobierno de México, 2022, 2024), which may inspire and motivate young women from this region of the country.

TABLE 1 Academic staff and undergraduate and graduate students in Juarez Autonomous University of Tabasco (UJAT) educational programs in Science Technology Engineering and Mathematics (STEM) areas (Narváez Osorio, 2024).

| Level of participation | Women | Men |
|---|---|---|
| Undergraduate students | 1,903 | 3,892 |
| Graduate students | 162 | 201 |
| Academic staff* | 260 | 475 |
| Total | 2,325 | 4,568 |

*Includes tenures, temporary, and part-time professors.

The UJAT, being the most important academic Institution in the state, contributes to this statistic with 218 researchers, but only 77 of them are women (35%), which agrees with the local statistics. But more important is the fact that until July 2024, from the 24 researchers with higher SNII levels of the UJAT (Levels II and III) only seven are women (29%) (CONAHCYT, 2024), which reflects the low access of women from the entity to high levels of recognition.

According to data from UJAT (Narváez Osorio, 2024), the number of women working in STEM areas within the UJAT (Universidad Juárez Autónoma de Tabasco) is lower than the number of men (Table 1). In postgraduate and undergraduate programs, the data are very similar. This can be interpreted as the need for incorporating more women in these areas.

Since the UJAT offers careers according to the needs of the state, it is necessary to promote higher participation of women in STEM areas. However, other factors such as customs and traditions from the region which are related to the historical belief that women should stay at home and take care of children and husband, low family incomes, long commutes because transportation routes are not well-developed and there many people live in remote communities, and the lack of awareness of opportunities have a detrimental effect on such enterprises. As a strategy to contribute to diminishing the gender gap, the UJAT implemented the Institutional mentoring program for women in STEM, which recruited 30 participants to boost the professional goals of students and teachers from the UJAT, with the collaboration of the British Council. In this work, the role of social technologies such as online training, virtual meetings, and social networks is crucial. These technologies facilitate communication, knowledge sharing, and goal reinforcement, thereby advancing and achieving the mentee's goals and reinforcing leadership in mentors.

# 2 Methods

## 2.1 Social technologies used

The social technologies employed for this study were social media (Facebook, X, Instagram, and WhatsApp) for dissemination of the program and to establish the network for direct communication between the participants and the research group in charge of the study, collaborative online tools (Jamboard,

mentimeter and Microsoft Teams), and an e-learning platform (*Vincúlate*).

## 2.2 Selection of the participants

Recruitment of the participants was performed through an open call, which was disseminated through social media, and using UJAT's radio and TV channels. To reinforce this, on-site visits to the different campuses of the university were carried out with the support of the authorities, where all the information related to the call was provided and to recruit potential candidates. Inclusive language as used in the call. The applicants filled in an online form that included the following aspects: privacy notice, general information of the participant, interest in participating, expectations of the program, and experience. The criteria for selecting the applicants were the following: (i) to be women working on STEM areas, (ii) to be members of the university either full-time or mid-time professors or enrolled students in undergraduate or postgraduate studies, (iii) to be willing to take the training, and (iv) to meet the expectations of the program. An additional criterion for mentors was the experience in calls for getting funds, and the recognition in their fields, which was confirmed by their CVs and the corresponding evidence. After selection, the applicants were asked to confirm their participation by email. Thirty participants (14 mentees and 16 mentors) confirmed their participation and were selected and split into two groups (mentors and mentees) according to their needs, experience, and objectives.

## 2.3 Mentoring training

Once selected, the participants were trained in mentoring for 2 months. The training consisted of an online course (MOOC) integrated into five modules and four sessions of accompaniment with a duration of 90 min each. All the topics revised in the MOOC, were provided by the British Council though the *Vincúlate* platform, and were in Spanish, although some of the complementary materials (videos, webinars and readings) were in English but translation to Spanish was available. During the training, virtual meetings, social media, videos, and collaborative apps were used to encourage participants to increase their communication skills as well as their tools for developing the mentoring process. Two instructors carried out the accompanying tasks using the virtual Microsoft Teams platform. Collaborative tools used during the meetings included Jamboard (google), whiteboard (Teams), and mentimeter. Communication was accomplished using instant messaging.

## 2.4 Matching

A matching process was performed using a questionary to find as many coincidences as possible between mentor-mentee regarding professional objectives, experience, availability, willingness and hobbies. To avoid biases, the pairs were formed avoiding matching participants that belonged to the same campus or educational program. With this, 14 mentees were matched up with 14 experienced mentors. The number of pairs was limited by the number of mentees. The mentors that were not matched (two), were considered as substitutes if needed, after asking them for willingness to do so. The results of the match were communicated via e-mail and a further brief person-to-person meeting to establish the rapport between the mentor-mentee dyad.

## 2.5 Mentoring relationship

The mentoring process took place over a period of 12 weeks, where one-on-one meetings took place once a week. In between sessions, mentees worked on the objectives that they had established at the first meeting. All mentees were asked to establish their own objectives using the SMART (Specific, Measurable, Achievable, Relevant, Time-based) approach. The progress of the objectives was monitored through a personal diary during the mentoring sessions, and the performance of each participant was assessed using a feedback form. This feedback form included general data such as date, and the name of the counterpart in order as evidence of that the meeting took place. The evaluation of soft skills was estimated using a self-assessment form before and after the conclusion of the mentoring. During this stage of the program, a drawback took place between one of the pairs and did not conclude the relationship.

## 2.6 Assessment of the program

Finally, after the mentoring relationship concluded for the 13 pairs, mentors (15, considering the un-matched mentors) and mentees (13) evaluated the program through an assessment questionnaire filled in online that included the following sections:(i) staff's performance, (ii) the suitability and opportunity of the call, (iii) the program's contribution to achieving the objectives established by the mentees, and (iv) the benefits obtained as participants. The questionnaire used for the assessment of the program was bases on the evaluation form used by the British Council and Inova Consultancy during the training of the staff prior to the implementation of this program, with modifications to align it with the needs of UJAT. For the analysis of the results, four key questions related to the main objective of the program and social technologies were selected.

# 3 Results

## 3.1 Training phase

It is worth mentioning that from the selected applicants, not all of them completed the confirmation for taking the training, without providing any reason, this was an expected result as the schedule of applicants and priorities may change during the process. The program's population included participants from different locations in the state. Therefore, the use of virtuality, social media, and instant messaging played a key role in the communication and dissemination of the program results during the training.

Since the accompaniment sessions were used as a strategy for reinforcing and discussing the topics revised in the online course, the use of collaborative applications allowed us not only to obtain information about the progress of the participants but also to gain knowledge on the compromise and particular obstacles that were faced by the participants regarding their everyday activities, which will imply further modifications to avoid work overload. Taking the training online and asynchronously allowed the participants to keep their own pace and progress according to their schedules. The overall result was the completion of the training by 100% of the participants in 8 weeks ± 5 days.

## 3.2 Mentoring relationship

One key activity was to establish the goals that the mentee wanted to achieve, and the use of SMART objectives methodology was promoted. At the end of each meeting, each participant filled out the feedback form for their counterparts about their performance as mentor/mentee, and the forms were sent by e-mail. At the end of the mentoring, 100% of the participants filled out the forms, although just 50% sent them on time (during the first 2 days after each meeting), whereas the other 50% of the participants had delays in the sending from 1 to 14 days. During session 12, each mentee was asked by her mentor to evaluate the achievement of their objectives.

The mentoring relationship lasted approximately 3 months with periodical meetings once a week. Despite the general advice for the participants was to have meetings with enough time to allow the reaching of weekly planned activities, it was observed that as the end of the semester approached, which coincided with the last month of the relationship, the meetings were re-scheduled, or the period was different (larger or shorter than at the beginning). This information was collected from the feedback forms sent to the participants.

## 3.3 Assessment of the program

To assess the effectiveness of the program, surveys were conducted among mentors and mentees, which included sections on their overall opinion about the program, this included whether the call was clear, suitable and properly scheduled, how they felt about the mentoring relationship, and general perception of the program and they were asked to leave any additional suggestions or comments to improve the program. It should be mentioned that during the mentoring stage, one dyad experienced lack of rapport after the third meeting and they decided not to continue, then only 13 pairs completed this stage. Regarding the launch, suitability and schedule of the call, as well as the kickoff ceremony, the results (Figure 1) showed a favorable reception, for both mentors and mentees.

Even though no unfavorable responses were obtained in the first part of the questionnaire, it is observed that some opinions differ between mentees and mentors. For example, mentees noticed less clearly the criteria for selection whereas according to mentors, the dates established in the call were not completely adequate or met. These aspects can be improved in further calls.

Figure 2 shows the opinions provided for the participants with the role of mentors. According to their responses about the training, 100% were favorable options ("Strongly Agree" and "Agree"). Despite the encouraging of these results, it should be noted that the number of sessions and the contents revised are areas for improvement in further calls, as the participants responded not to be totally convinced. Regarding the platform where the contents of the training are allocated, most participants considered it easy to use.

On the other hand, the responses for this topic provided by mentees (Figure 3) showed that for mentees the number of accompaniment sessions needs attention, since responses were more varied than those provided by the mentors.

During the training period, mentees were provided with two accompanying sessions, each lasting 90 min. Most of the participants indicated that they totally agreed on the duration (84%), with a variation of opinions in the number of sessions (69%). It is noted that for the mentees, the number of accompaniment sessions could be increased or improved in further calls. Also, it was observed that as for mentors, the use of the e-learning platform was easy to manage for the mentees too. Interestingly, regarding the tools provided during the training, considering "Totally agree" responses, almost half of the mentees agreed that they were enough to identify the limitations or barriers that they face by being involved in STEM areas, since half of the mentees responded just as "Agree," this may indicate that it is needed to develop additional tools for helping mentees to identify their own limitations needs in further trainings.

One of the main objectives of the program was the achievement of the professional goals of the participants. In this regard, they were asked about in what degree they considered their SMART objectives were accomplished. The results are shown in Figure 4, and there it can be observed the differences in perception. Whereas the mentees felt more optimistic as most of them considered to reach more than 80% of their SMART objectives, mentors did not share the same opinion in two cases. Just one of the mentees considered to achieve their established objectives in a low percentage.

The last result that is worth discussing is related to the obtained benefits after conclusion of the program. Here is needed to say that for mentors, this was a multiple-choice question because there were well-established skills that will be reinforced for the mentors, but for mentees their opinion about the benefits was an open question to get more information about their point of view. The results are displayed in Figure 5 as a word cloud.

Interestingly, most of the mentors agree that their mentoring skills were improved, followed by the reinforcement of leadership, while the active learning was also among the most common responses. As can be observed in Figure 5B, mentees felt benefited because the mentoring helped them to organize their time and improve their ability for planning, which also contributed to the achievement of their goals. At the end of the program, some of the participants were asked to volunteer to create short videos about their experience as part of the program, as most of the volunteers declared, significant improvements in active listening skills (mentors) and greater clarity in setting career goals (mentees) were achieved at the end of the relationships.

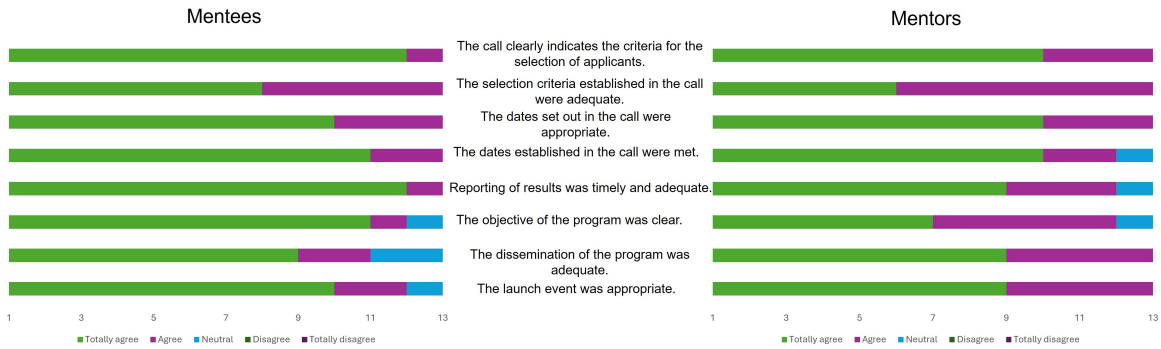


FIGURE 1
Overall opinion of the participants regarding the call.

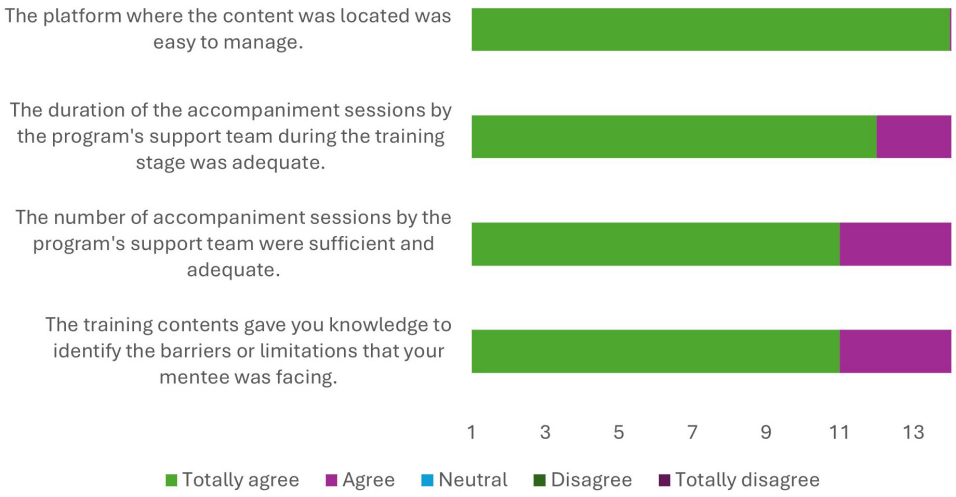


FIGURE 2
Mentor's opinions about the training.

## 4 Discussion

Gender gap is remarkably noticed in the southeast of Mexico, where customs and manners still limit women's development. Besides cultural beliefs, women in this region of the country must overcome difficulties such as harassment, economic and social limitations for having access to higher academic degrees that allow them to get well-remunerated jobs.

According to the overall impression of the participants, the launch of this mentoring program helped the participants in different areas of their life. The use of online platforms is an alternative tool for women for training. Nevertheless, the lack of funds and awareness of opportunities limits women in Tabasco. As observed from the recruiting stage, where on-site meetings with potential participants took place, one common concern arose: this type of programs should be available not only for women but also for men, since the lack of opportunities is generalized due to centralization in Mexico.

The use of social media helped to disseminate the call, nevertheless due to the high number of activities at the University, the information is lost among so many advertisements. This is probably one of the reasons why the participants noticed that the call was not as good as it should be in terms of schedule, dissemination and general information. In this regard, it is advisable to search for additional strategies such as the creation of media allusive to the program that can be broadcast on TV and radio. One additional strategy to reach more potential applicants could involve the participation of mentors and mentees from the first call to share their experiences through short videos, interviews and in-person conferences.

It was observed that training was a key stage for the success of the program, but there were different scenarios that should be considered for further calls. According to the assessment questionnaire, the use of MOOC was not difficult either for mentees or for mentors, but the need to schedule more and longer accompaniment sessions arose. This may be due to the lack of knowledge of what mentoring is. UJAT offers "academic mentoring" which is provided by students to students for specific topics, and offers "tutoring" also, where professors provide guidance to students during freshman and sophomore. Even though the objective of those programs is different to the mentoring for women in STEM, some strategies and actions are shared among the three programs, which facilitates the transition to mentoring


FIGURE 3
Mentee's opinions about the training.

for achievement of professional goals. This was reflected in the use of asynchronous platforms, social media and other tools for establishing good communication and scheduling meetings for mentoring. It was observed that those pairs that met more than twice in person, experienced better rapport as the participants externed during the accompaniment sessions.

It is worth noticing that the achievement of the SMART objectives was differently perceived by mentees and mentors. This could be explained by two different scenarios observed during the accompaniment sessions during training with the mentees: (i) the mentees noticed a significant change in their organizing and planning activities which lead them to consider that they made a lot of progress in achieving their objectives, or (ii) the improvement in their skills to establish clear goals making them to be more focused and thus they may perceive this as an approaching to the objective. Either way, this lets us think about the need to develop a quantifiable and unbiased tool or instrument that allows us to measure the real achievement of the objectives soon.

In Tabasco, development opportunities are lower compared to northern and central Mexico, besides the lack of awareness about application procedures, and how to get financial support, significantly reduce women's opportunities of aspiring to higher positions, scholarships, and resources. In the Academy, participation in funded projects, collaborative scholarships, and scientific products are critical to accessing the National System of Researchers and federal scholarships that impact women's income. In this sense, the UJAT mentoring program was focused on addressing these and helping women learn about and strengthen their skills in specific areas that help them advance their careers, mainly as researchers. As stated in the assessment questionnaire, some of the participants in the role of mentees concluded personal projects after the mentoring (enrolling in postgraduate studies, finish a paper or concluding their experiments for theses) that were boosted by the accompaniment of their mentors. We expect this success will help to promote future calls, increasing the number of applicants and thus the number of participants.

At the beginning of the training, the lack of self-confidence was the common characteristic among the mentees, but once concluded, most of the participants felt more confident not only at personal level but also as professionals since they are now aware of their strengths and weaknesses, but more important they are willing to change their situation by acting and stepping out of their comfort zone.

The UJAT mentoring program emphasizes the importance of unity and empowerment among women. In addition, networking was promoted not only by providing a space for technical knowledge sharing but also by creating a trusting environment in which women can freely discuss the specific obstacles they face and work together to overcome them.

Creating these networks is vital to breaking down the barriers of isolation that many women experience in STEM in the southeast of the country. By having a mentor who understands common STEM challenges, mentees can feel empowered to advance in their careers. This support is essential to increasing the retention of women in technology and science careers at UJAT, where dropout rates are high due to a lack of support.

Mentoring through social technologies has a transformative impact on creating a culture of support among women, especially

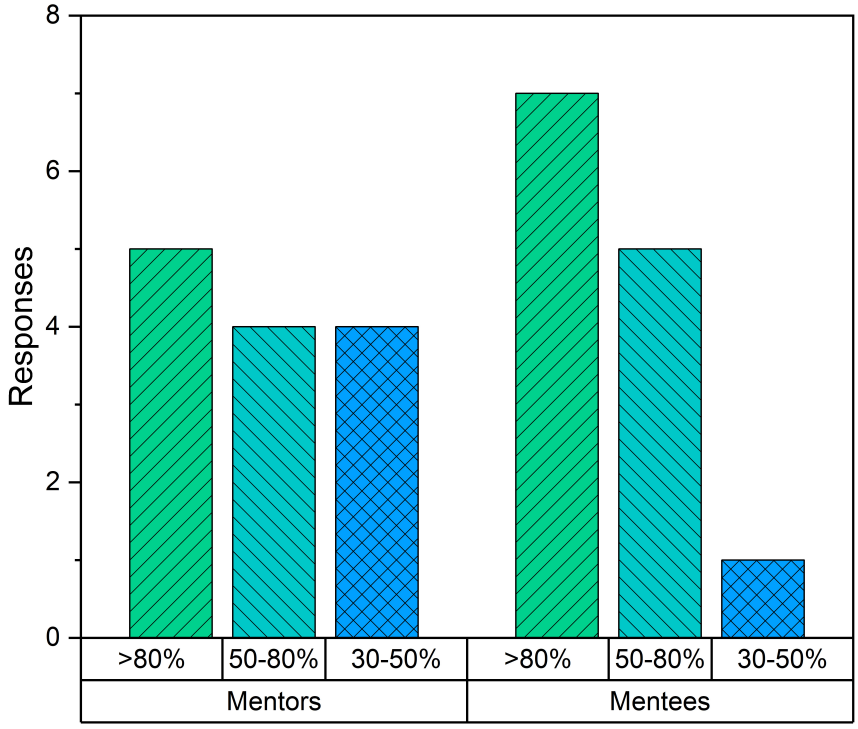


FIGURE 4
Achievement perception of the SMART objectives by mentees and their corresponding mentors.

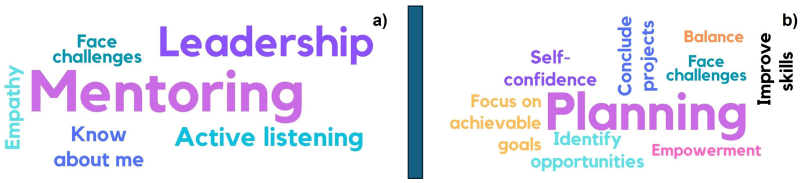


FIGURE 5
Benefits obtained by the participants after the conclusion of mentoring relationships. **(A)** Mentors and **(B)** Mentees.

those beginning their professional careers (Brizuela et al., 2023). As these women advance in their careers, they can become mentors, creating a virtuous circle of inclusion and support within STEM careers.

The UJAT mentoring program, and its alignment with social technologies, understood not only as social media but also as all type of technologies used for women in this program such as collaborative applications, videos, vlogs, and repositories, generates a supporting infrastructure designed to drive women's inclusion and professional development in STEM. This takes significance because as previously described, in Tabasco the insufficiency of transportation directly affects the mobility, and limits the opportunities for specialized training, and improvement of skills in women. Through social technologies, the participants of this program learn synchronously and at their own pace fundamental concepts not only for mentoring, but also to understand the context in which a mentoring program is needed. Technology tools have opened a wide range of opportunities, but it is needed to establish programs for women to use these tools for their own benefit and to increase they collaboration through networking. By providing a network of mentors, this program not only trains participants in technical skills but also provides them with the tools to face and overcome structural barriers that have limited their participation in these areas.

According to the observed results, the implementers have noted that the accompaniment was effective in most cases, as the mentees are now aware of their skills and must continuously work to improve themselves. The second finding is related to the necessity of setting clear objectives based on a previous evaluation of the mentees' professional status and priorities. In addition, the use of social technologies to increase their collaborative network will be a milestone in their careers.

The program has revealed the potential for a hybrid model, where face-to-face sessions and social technologies play a key role in effective training and communication. This innovative approach opens new possibilities for the program's future, making it more adaptable and accessible. In addition, areas for improvement have been identified, such as the need for more training tools and periodical meetings for the participants to get feedback from their partners.

## 5 Conclusion

The UJAT mentoring pilot program has proven effective for promoting women's inclusion in STEM careers, improving their professional skills, and expanding their network. Mentors consolidated their positions, felt empowered, and were proud to promote the growth of mentees. Most mentees left their comfort zone and achieved their goals; some even surpassed themselves.

The pilot program yielded good results, and improvements such as extended mentoring sessions, additional training with an emphasis on soft skills, and a focus on including more areas of knowledge are proposed. Accompaniment is crucial during training, but also continuous supervision of the progress of each dyad is needed. This case study highlights the critical role of social technologies for inclusion in sectors where women have traditionally been under-represented. The mentoring approach used in the program can provide a basis for future policies and programs at the regional level. Before implementation in other locations, institutional/organizational support is the first goal for the team, and it is also essential to link with NGOs or local sponsors to get fundings and support. Fundings will be needed for organizing in-person meetings for the participants, whereas support provided for any other actor of the society will increase visibility and dissemination of the program. Another critical requirement is to align the objectives of the mentoring program with the priorities and needs of the Institution/Organization, so it is recommended to perform a SWOT analysis. As those needs evolve and the results of the mentoring program contribute to reach institutional goals and objectives, the program will become part of the Institution/Organization's policies. Another recommendation is to hold in-person meetings once or twice during the process for mentors and mentees separately, because it will encourage peer-to-peer feedback while at the same time this will be an additional strategy for monitoring the mentoring relationships.

Since this manuscript describes the first institutional approach to a mentoring program for women in STEM, some limitations regarding the staff arose. Even though this program was designed for women in STEM, experts from social sciences are needed. It is suggested that the staff be reinforced by including personnel with experience in gender and inclusion affairs, for supervising the contents of the training materials and the further reports that will be generated. Psychologists are also required to modify the evaluation instruments to obtain more information related to personal challenges that the participants face in their role as housewives, mothers, and/or heads of family, psychologists can be helpful also to design tools used during the training. Because one of the aims of the mentoring is to give visibility to women and their achievements, its is necessary to incorporate also specialists in communication for attracting more participants by designing visually attractive, impactful materials for social technologies and clearly communicates the objectives and results of the program.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in this article/supplementary material.

## Ethics statement

The requirement of ethical approval was waived for the studies involving humans because personal data of the participants is reserved. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin because data were obtained for statistics only and no sensitive information of the participants is disclosed.

## Author contributions

CP: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft, Writing – review and editing. MA: Conceptualization, Funding acquisition, Writing – original draft, Writing – review and editing, Project administration.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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# Empowering indigenous women in Guatemala: a case study of the role of Digital Community Centers in enhancing digital literacy and changing gender perspectives in Northern Huehuetenango

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**Introduction:** This study examines how Digital Community Centers (DCCs) contribute to the empowerment of indigenous Mayan women in Northern Huehuetenango, Guatemala. Although rural and indigenous communities remain largely excluded from digitalization, the DCC model aims to narrow the digital gap by providing internet access, basic computer training, and workshops on positive masculinities.

**Methods:** We employed a mixed-methods approach, including 10 semi-structured focus groups and 43 surveys. The survey assessed digital literacy and gender attitudes using the GNDR-4 and GEM scales.

**Results:** Findings show significant improvements in women's digital skills after a short training period. These gains enabled participants to reduce travel time for tasks such as processing government documents and to launch small-scale economic initiatives. Participants who attended the positive masculinity training—both men and women—reported more equitable attitudes toward women's leadership and decision-making.

**Discussion:** Despite these gains, participants stressed ongoing barriers—most notably limited infrastructure, constrained financial resources, and insufficient institutional support—that hamper the long-term viability of the DCCs. They also noted a need for more detailed and standardized training on gender topics to sustain changes in attitudes over time. In conclusion, DCCs offer a promising strategy for bridging the digital divide and facilitating women's socio-economic participation, but further research with larger samples and longer follow-up periods is warranted to confirm and expand upon these initial findings.

KEYWORDS

**Mayan women, women's empowerment, digital skills, GEM scale, GNDR-4 scale**

## 1 Introduction

Digital literacy and access to technology are powerful catalysts for social and economic development, affecting everything from education to healthcare and beyond (World Bank, 2016; UNESCO, 2015). However, a profound digital divide persists, particularly in rural and marginalized communities, hindering access to essential resources and creating additional barriers for women (Hafkin and Huyer, 2006). These challenges become even

more acute in indigenous settings, where historical inequalities and limited infrastructure further restrict women's educational and economic opportunities (Zaremberg, 2024).

Although digital tools have shown their potential to bolster growth and reduce poverty, rural communities often remain on the periphery of such advancements (Van Dijk, 2006; Hilbert, 2011). Poor infrastructure, scarce financial resources, and lower educational attainment contribute to systemic cycles of marginalization. In response, Digital Community Centers (DCCs)—also referred to as telecenters—have emerged as a viable approach to bridging the gap. By situating internet connectivity, computers, and training programs directly within underserved communities, DCCs help address logistical barriers and foster community engagement (Barton and Bear, 1999; Bailey and Ngwenyama, 2013). This can be particularly impactful for women, who face additional cultural and socioeconomic constraints that limit their ability to benefit from digital technologies.

This study focuses on the remote Chuj region of Huehuetenango, Guatemala, to examine how DCCs advance indigenous women's empowerment. Specifically, we ask: how does access to the internet, digital literacy contribute to the empowerment of indigenous women in rural Guatemala? Empowerment, particularly for women in rural contexts, is commonly defined as a process through which individuals gain the ability, resources, and agency to make strategic life choices (Kabeer, 1999). In this study, we conceptualize empowerment both at the individual level—where new digital skills enable women to manage administrative tasks, acquire and share knowledge, and assume leadership roles—and at the collective level, where stronger relationships emerge among female leaders, local authorities, and educational institutions. We address this question by drawing on a mixed-methods approach that captures both the qualitative experiences of indigenous women and the quantitative shifts in empowerment-related indicators. Our contributions are threefold: (1) shedding light on an often-overlooked demographic—Mayan women in remote rural settings; (2) extending the discourse on how digital education intersects with women's agency in contexts shaped by limited resources; and (3) offering a combined qualitative-quantitative analysis that helps illuminate the nuanced impact of DCCs under real-world constraints such as small sample sizes, language barriers, and sporadic community engagement.

The remainder of this paper is structured as follows: we begin with a description of our methods, detailing the selection of participants, data collection procedures, and analytical techniques. We then present the findings, first from the qualitative analysis of focus group discussions, followed by the quantitative assessment of changes in digital literacy and women's empowerment. Finally, we discuss the broader implications of these results for sustainable, community-led development, acknowledge limitations, and propose directions for future research.

## 2 Background

Numerous studies underscore the transformative potential of telecenters, also known as Digital Community Centers (DCCs), in bridging the digital divide and fostering socio-economic development in rural areas. Telecenters not only grant internet connectivity and access to information but also serve as platforms for community capacity-building, thereby encouraging education and economic activities (Díaz Andrade and Urquhart, 2009). In Latin America, early work highlighted how telecenters boosted digital inclusion and advanced social services in underserved regions, offering critical resources and skills to local populations (Proenza et al., 2001).

Within Central America, specific initiatives illustrate the varied ways DCCs can drive rural development. Panama's InfoPlazas and Costa Rica's Intelligent Community programs, for instance, demonstrate measurable improvements in digital literacy and entrepreneurial activities in remote communities (Proenza et al., 2001). Their successes underscore that strong community involvement, combined with partnerships involving local organizations, is vital for sustaining telecenter projects (Cecchini and Scott, 2003). These programs also show that targeting women's participation is particularly critical, as persistent cultural norms and limited mobility can otherwise curtail women's access to technology (Hafkin and Odame, 2002).

Empowering women and girls through digitalization is broadly recognized as an essential strategy for inclusive development. When women gain digital skills, they are better positioned to participate in the workforce, access health information, and advocate for their rights (Heeks and Molla, 2009). Nonetheless, multiple challenges persist, including financial barriers, inadequate infrastructure, and prevalent stereotypes that constrain women's entrepreneurial ventures (Akpuokwe et al., 2024). Further complicating the picture, sociocultural beliefs about gender roles can shape everything from pro-environmental behaviors (Xia and Li, 2023) to political participation and online safety (Setiyaningsih et al., 2023). Taken together, these factors highlight the need for gender-responsive policies and training that address the specific contexts and obstacles rural women face.

Measurement tools like the Gender Equitable Men (GEM) and GNDR-4 scales offer insights into changes in household, economic, and political empowerment—factors that can be directly influenced by DCC-based interventions. Hilbert (2011) found that women's access to information and communication technologies boosts economic and political engagement in rural communities. Likewise, Proenza documented how telecenters in Latin America equipped women with new skills and pathways to local governance, emphasizing telecenters' role in bridging the gender digital divide. Additional research reveals that digital competencies can serve as a powerful mechanism for upward mobility among other marginalized groups as well (Liu et al., 2024; Worcester, 2021), suggesting the broader applicability of DCC-based models that integrate skill-building, community engagement, and ongoing support.

While this study specifically focuses on Northern Huehuetenango, it is important to note that New Sun Road (NSR) has also implemented solar-powered, internet-enabled DCCs elsewhere in Guatemala—particularly in Alta Verapaz and Quiché. Across these broader initiatives, NSR has reached more than 4,000 Q'eqchi', Chuj, and Ixil-speaking women, offering digital skills training and promoting gender-equitable norms. Although these other regions are not included in the current analysis, they provide a valuable context: past successes and lessons learned reinforce the potential for DCCs

to empower rural communities in diverse sociolinguistic and geographic settings.

# 3 Data and methods

Our data comes from two sources, interviews and surveys that aim to answer the main research question: how do Digital Community Centers contribute to the increase in digital skills and change in gender perspectives among indigenous women in Northern Huehuetenango? Field staff from New Sun Road, who share the ethnic background and language of participants, conducted the surveys in person, and the interviews online. One of their primary responsibilities was to ensure that participants clearly understood each question. The field staff collected responses verbally and organized them in a spreadsheet. All participants provided informed consent, and steps were taken to ensure their confidentiality and anonymity throughout the study. The role of the field staff was crucial because of the trust they had built through the broader Mujer Prospera project, under which the surveys and digital tests were administered. This trust was vital for addressing sensitive gender-related questions in rural areas where traditional gender norms often prevail.

## 3.1 Qualitative approach

This study employed a qualitative methodology to explore participants' experiences with the Digital Community Centers (DCCs) in Guatemala and to gain deeper insight into shifting gender perspectives and digital inclusion in indigenous communities. Through semi-structured focus group interviews, we aimed to understand the perceived impact of the DCCs, areas for improvement, collaboration among community members, and local priorities related to digital skills and gender norms. These focus groups provided a space where participants could express their views collectively, fostering an environment that encouraged dialogue and reflection on shared experiences. The decision to conduct focus groups rather than individual interviews was based on the understanding that participants generally feel more comfortable speaking in a group setting. However, we remained aware of potential group leader bias, where dominant voices might influence the discussion. To mitigate this, facilitators were trained to ensure that all participants had the opportunity to share their perspectives, using targeted follow-up questions and structured turn-taking strategies.

A total of 10 focus groups were conducted, comprising 33 Mayan women and 10 Mayan men, all of whom were 18 years or older. Participants were selected randomly from 10 different communities in Huehuetenango, ensuring representation across diverse community settings. The sample included community leaders, members of the Women's Leadership Committee (WLC), and other key stakeholders who had benefited from the DCCs and had varying degrees of involvement in leadership and training initiatives. The focus group discussions were conducted virtually via Google Meet, allowing participants to join from their respective DCCs while minimizing travel burdens. To accommodate linguistic diversity, staff from New Sun Road provided live interpretation from Mayan Chuj to Spanish, ensuring accurate communication and comprehension. Facilitators were trained in culturally sensitive interviewing techniques to encourage open dialogue and minimize potential power imbalances that could arise in discussions about gender norms and community leadership. In addition, focus groups with women were led by indigenous female facilitators, while groups with men were led by indigenous male facilitators, ensuring that discussions took place in a setting aligned with participants' cultural and gender-specific comfort levels.

In determining the number of focus groups, we continued recruitment until thematic saturation was reached—that is, until new data no longer yielded additional themes. Recruitment also involved consultation with local community leaders to ensure a diverse range of ages, marital statuses, and leadership backgrounds among participants. All procedures received ethical clearance, and each participant provided informed consent before the session commenced. Where literacy levels were low, the study team read consent forms aloud and answered questions to ensure full understanding.

Each session began with an introduction and an icebreaker activity to establish rapport and ease participants into the discussion. The facilitators then guided the conversation in the native language using a semi-structured interview format, starting with broad, open-ended questions, and progressively narrowing the focus toward more specific topics related to the DCCs' benefits, gender dynamics, and digital literacy challenges. This approach allowed participants to share their perspectives freely while also ensuring consistency across focus groups. The interview guide, which included key questions and themes explored during the discussions, is available in the Supplementary material. Participants were given explicit assurances of confidentiality, and permission for recording was obtained at the beginning of each session. Discussions were audio-recorded and later transcribed for analysis.

A thematic analysis approach was employed to identify recurring patterns in participants' responses. The transcriptions were coded using an inductive-deductive hybrid approach, where inductive coding allowed themes to emerge directly from participants' narratives, while deductive coding was guided by key research questions on gender norms, digital literacy, and community engagement with the DCCs. Two independent researchers reviewed the transcripts and applied coding frameworks to enhance intercoder reliability and ensure the robustness of the analysis. The findings revealed several key themes, including the perceived benefits of the DCCs, such as increased access to technology, improved digital skills, and greater confidence in using digital tools for communication and employment. Challenges and barriers also emerged, particularly regarding connectivity issues, limited local expertise, and persistent gender-based constraints that affected women's ability to participate fully. The discussions also highlighted shifts in gender perspectives, particularly regarding shared responsibilities in digital literacy training and evolving attitudes toward leadership roles for women in the community. Additionally, participants emphasized the importance of community-led solutions and sustainability, noting that long-term success would require

local ownership, continued training, and ongoing support from community organizations.

By integrating virtual focus groups, multilingual facilitation, and a structured analytical approach, this qualitative component provided rich, context-specific insights into how digital literacy initiatives intersect with gender equality and digital literacy efforts in indigenous communities. The findings complement the quantitative survey data, offering a nuanced understanding of how digital and social interventions interact in rural Guatemala.

## 3.2 Quantitative approach

For our quantitative analysis, we surveyed 10 men and 33 women who self-identify as Mayan. The field staff administered two surveys—the Gender Equitable Men (GEM) scale and the Gender Equality (GNDR-4) scale—with baseline data collected in October 2022 and endline data in August 2023 under the USAID-funded Mujer Prospera project in Huehuetenango. The same respondents participated in both baseline and endline for these scales. For the digital test, we only included women who took part in GEM and GNDR-4, totaling 29 women at baseline and 32 at endline. The baseline for the digital test was collected in October 2022 and the endline in August 2023, also as part of USAID-Mujer Prospera, administered exclusively to women because they were the project's main beneficiaries and the ones receiving the digital skills training.

The intervention included training on positive masculinities, intended to shift attitudes toward gender roles, and a digital skills training program that spanned roughly 3 months. In these traditional communities, the workshop discussions primarily framed "women" from a biological perspective, reflecting local cultural norms, and practices. The positive masculinities training was based on deconstructing traditional mandates associated with hegemonic masculinity, emphasizing shared responsibility and respect for women's rights. Through participatory activities, it highlighted how certain gender roles perpetuate inequality and how challenging they can foster more equitable, violence-free relationships. The session also underscored the need for everyday practices that support social justice and equality, urging both individual and collective commitment to transforming patriarchal structures.

The digital skills curriculum was designed to improve proficiency in communication, information, problem-solving, and content creation, following Eurostat's Digital Skills Indicator (European Commission, 2015) framework. Participants learned how to use basic Microsoft Office tools, navigate the internet, perform Google searches, handle government documentation online, and even experiment with emerging AI applications, such as ChatGPT and Bing, for daily tasks.

The digital literacy test administered by the field staff was adapted from the Eurostat Digital Skills Indicator (European Commission, 2015) to capture foundational digital competencies in rural communities where routine access to computers and the internet can be limited. To accommodate the linguistic and cultural context, the field staff conducted the test orally in participants' primary languages, ensuring they fully understood each question or task. Participants were asked about specific activities they had performed in the past 3 months across four key domains—information, communication, problem-solving, and content creation.

1. **Information** included tasks such as conducting online searches or identifying reliable digital sources.
2. **Communication** encompassed activities like sending messages via email or chat platforms and participating in video calls.
3. **Problem-solving** covered using digital tools to address everyday challenges—e.g., filling out online forms, locating government services, or troubleshooting basic technical issues.
4. **Content creation** involved creating or editing documents, spreadsheets, or other digital materials that went beyond simple data entry, reflecting a higher skill level.

Each domain was evaluated on a three-tier scale—"none," "basic," or "above basic"—depending on whether and how many domain-specific tasks participants reported completing. When participants indicated they had never performed a given task or lacked the resources to do so, they were classified at the "none" level. Those who had done at least one relevant activity were typically classified as having "basic" skills, while those who performed tasks requiring more advanced functions—such as editing documents collaboratively, creating presentations, or handling more complex online processes—were placed at the "above basic" level. These domain-specific scores were combined into an overall digital skills assessment that reflects participants' general competencies. Because the Eurostat methodology emphasizes performance on tasks completed within the last 3 months, it was better suited to documenting the practical digital experiences of our participants.

To assess shifts in gender perspectives, we utilized two validated survey instruments to measure changes in participants' gender-related attitudes and evaluate the impact of an intervention aimed at fostering gender equality and promoting positive masculinities. Please refer to Supplementary material for the full methodology and questions on each survey. The first instrument was the Gender Equitable Men (GEM) Scale, adapted to measure progress toward one the key performance indicators for the Mujer Prospera Project: the percentage of women and men trained who demonstrate attitudes supportive of more equitable gender norms. Originating from a widely validated, cross-cultural scale, the GEM Scale assesses attitudes across multiple domains, including gender roles, sexual behavior, violence, masculinity ideals, and reproductive health. For each domain, statements such as "The most important role of a woman is to take care of her home and cook for her family" or "A woman should tolerate her partner's violence to keep her family together" are presented, and respondents indicate their level of agreement on a Likert-type scale (e.g., *totally agree*, *somewhat agree*, or *disagree*). Each answer is then assigned a point value, with higher scores signifying stronger support for gender-equitable norms. Summing individual responses yields a composite score, which can then be converted to a 0-to-1 range (0 = extremely low support for gender equality; 1 = extremely high support) for ease of interpretation. This transformation facilitates tracking of overall change and simplifies reporting to funding agencies. In line with the recommended approach from the original GEM methodology, the total number of items was culturally adapted to reflect local priorities and norms without overburdening respondents.

The second instrument used was the GNDR-4 Survey, known as the "Equal Opportunity Survey," which aligns with other key performance indicators for the Mujer Prospera Project: the percentage of participants who report increased agreement that men and women should have equal access to social, economic, and political resources. The survey presents three key statements, including (1) "Women should have the same rights as men and receive the same treatment," (2) "In general, men are better political leaders than women and should be elected instead of them," and (3) "When jobs are scarce, men should have more right to a job than women." Respondents rate their agreement on a four-point scale (e.g., *totally disagree* to *totally agree*). Each item is coded from −2 (totally disagree) to +2 (totally agree), with statements marked "(r)" scored in reverse so that higher totals consistently denote more egalitarian attitudes. The summed score can then be compared between baseline and endline to evaluate changes in participants' views of gender equality.

Both surveys were administered at two time points (pre- and post-intervention) by trained field staff who shares the language and cultural background of the participants. This was critical for establishing rapport, ensuring respondents understood each item clearly, and maintaining confidentiality—especially important when covering sensitive topics such as gender violence, traditional norms, or personal beliefs about masculinity. For participants with limited literacy, enumerators read questions aloud in their local language, and recorded responses to mitigate misunderstandings. Each respondent's data were entered into a secure database, and personally identifiable information was masked or encrypted to preserve anonymity.

This study employed a before-and-after design to evaluate shifts in both gender-related attitudes and digital competencies, using the same participants at baseline and endline for a paired analysis. A total of 43 respondents (33 women and 10 men) provided complete data for the GNDR-4 and GEM scales, while 32 women participated in the digital skills assessment at both time points. The GNDR-4 and GEM surveys measured various dimensions of gender equality, masculinity, and violence, whereas the digital test evaluated communication, information, problem-solving, and software proficiency.

Although each survey item—and each digital skill category—was ordinal in nature, composite scores were generated for GNDR-4 and GEM by summing item-level responses, facilitating the calculation of average changes across sex, education, marital status, and parental status. For the digital test, individual skill levels also ranged from "none" to "above basic," enabling a paired comparison of pre- and post-intervention performance. By using these summative or ordinal measures, the analysis could capture overall shifts in attitudes and competencies, rather than focusing on individual item responses alone.

To test for statistically significant changes, the Wilcoxon Signed-Rank Test was applied to both the survey items (GNDR-4 and GEM) and the digital literacy categories. This non-parametric test is well suited to paired ordinal data and does not assume a normal distribution, making it ideal for evaluating pre- and post-intervention responses. The findings are illustrated in figures that display differences in gender attitudes and digital skill levels, offering insight into the extent and direction of change attributable to the intervention.

# 4 Results

## 4.1 The impact of Digital Community Centers through the lenses of Mayan women

This section presents the findings from focus groups conducted in several communities in Northern Huehuetenango, focusing on the impact and challenges of Digital Community Centers (DCCs).

The introduction of Digital Community Centers (DCCs) has significantly improved access to essential services, digital literacy, and economic opportunities across San Mateo Ixtatán and Nentón. The DCCs have provided crucial services such as energy and computer access, photocopying, and processing of government documents like birth certificates and national IDs, which have notably reduced travel time and expenses, particularly benefiting women with young children. One participant shared, "Before the DCC, I had to travel 4 h to get a document for my child. Now, I can do it in 10 min here in the village."

Beyond these essential services, the DCCs have played an important role in improving digital literacy and skill development, especially among women. This has empowered them to acquire new knowledge, manage local administrative tasks, and contribute more effectively to community development. "Before I did not know how to manage a computer, now we created a Facebook page to promote *El Cenote*....our touristic place." In some communities, the availability of energy through the DCCs has enabled new economic activities, such as small businesses that rely on electricity, further contributing to community empowerment. "Now, 23 are selling popsicles and renting the fridge for keeping birthday cakes refrigerated." During the rainy seasons, when home energy solutions are often limited, the DCCs have provided a reliable source of power and connectivity, underscoring their value in these remote areas.

Despite the clear benefits, several challenges were consistently identified across the communities. Many DCCs face significant resource shortages, including inadequate training for female leaders, limited internet connectivity due to the absence of hotspots, women leader's rotations due to migration, traditional gender roles, lack of time, or interest, and insufficient equipment. These limitations restrict the centers' ability to expand their services and meet the growing needs of the communities. For instance, one community member noted, "The people in the community want to have internet in their houses and the hotspot does not reach all the community."

Logistical issues, such as the need for physical infrastructure improvements—like installing secure doors or enhancing security measures—have also led to temporary closures and reduced the effectiveness of some centers. In two communities, a lack of commitment and communication between community leaders and the Women's Leadership Committee (WLC) was highlighted as a major concern, leading to inconsistent service provision and poor management. Furthermore, the transition of community leaders has, in some cases, resulted in a loss of engagement and support for the DCCs, weakening their impact and sustainability.

Using an inductive–deductive thematic analysis of focus group transcripts, we identified the theme of Collaboration

and Community Engagement as key to the DCCs' impact. During coding, participants' own words and narratives were organized under "community relationships," "local leadership," and "institutional support," allowing us to track how DCCs shape and are shaped by communal structures. On one hand, the inductive component enables codes and themes to emerge directly from participants' narratives, without imposing preconceived theoretical frameworks (Braun and Clarke, 2006). On the other hand, the deductive component is guided by predetermined categories and assumptions drawn from existing literature or specific research objectives (Fereday and Muir-Cochrane, 2006). By integrating both approaches, this analysis captures novel insights arising from the data while also assessing consistency with established theoretical constructs, thereby enhancing the study's overall validity and depth.

From these discussions, it emerged that DCCs have generally fostered improved communication and collaboration within communities, strengthening relationships between female leaders, local authorities, and educational institutions. This collaboration has been instrumental in advancing local development efforts. However, this positive impact has not been uniformly experienced across all communities. Some areas have reported limited engagement from local leaders and a lack of clear communication regarding the DCCs' progress and needs. As one leader remarked, "We need more consistent support and communication from our local authorities to keep the DCC running smoothly."

To enhance collaboration, participants consistently suggested increasing dialogue with schools to better promote the DCCs' services and involve a broader range of stakeholders in the decision-making process. "Now, we (the women's leadership) collaborate with the teachers to provide services to the students, also communicate with the Cocodes (community leaders) to provide support for their meetings; they are asking us to become part of the Cocode," noted one participant. By integrating direct quotations into our coded categories, we observed that establishing clear communication channels and assigning well-defined responsibilities are seen as crucial steps for sustaining the centers' positive impact and ensuring continued community support.

Although the primary focus of this research is on digital literacy and women's empowerment, participants consistently emphasized that reliable energy and small-scale economic ventures (such as selling cold products) are integral to making Digital Community Centers (DCCs) sustainable. From the community's perspective, access to energy not only supports the digital services offered but also creates local revenue streams that can, in turn, reinforce women's autonomy and decision-making.

To ensure the long-term sustainability of the DCCs, several key recommendations emerged from the focus groups. First, there is a strong desire to expand the range of services offered by the centers. Suggestions include introducing commercial activities, such as selling cold products that take advantage of the energy that the Centers have. Providing educational programs for children in collaboration with local schools was also mentioned. Only the DCCs with enough income for investment have been able to buy a fridge that responds to this request. Not in all the communities teachers and women's leadership committees have agreed to work together.

TABLE 1 Descriptive summary of sample.

| Demographic variable | Male ($n^a = 10$) | Female ($n^a = 33$) |
|---|---|---|
| **Marital status** | | |
| Married | 8 (80%) | 13 (39%) |
| Single | 2 (20%) | 20 (61%) |
| **Has children** | 8 (80%) | 13 (39%) |
| **Education level** | | |
| No education | 3 (30%) | 9 (27%) |
| Elementary incomplete | 4 (40%) | 6 (18%) |
| Elementary school | 3 (30%) | 15 (45%) |
| Middle school | 0 (0 %) | 1 (3%) |
| High school | 0 (0%) | 2 (6.1%) |
| **Ethnicity** | | |
| Chuj | 10 (100%) | 27 (82%) |
| Mam | 0 (0%) | 1 (3%) |
| Mestizo | 0 (0%) | 5 (15%) |

[a]n (%). Source: Authors' own calculations, 2023.

Enhancing internet connectivity by installing hotspots and upgrading the existing network, alongside providing additional training on how to use the internet for accessing information, and communicating with relatives and productivity, are considered essential steps to improve the quality and range of services. Furthermore, communities have emphasized the need for ongoing training and capacity-building for female leaders to ensure they can effectively manage the DCCs and continue to drive community development.

Finally, consistent engagement and communication between community leaders, the WLC, and local authorities were repeatedly emphasized as critical to the sustainability and growth of the DCCs. Implementing these recommendations will not only address the current challenges but also position the DCCs as central hubs for community development, ensuring they continue to deliver significant benefits to the residents of San Mateo Ixtatán and Nentón.

## 4.2 Women's empowerment and digital skills training and the subsequent changes in these communities

This section presents the quantitative results from the GNDR-4 and GEM surveys conducted in Northern Huehuetenango, as requested by USAID to assess the project's impact, along with the results from digital literacy tests. We analyze both pre- and post-intervention data across all three instruments and explore the association between women's empowerment and digital skills. Although the sample size is limited, requiring further observations, these initial findings offer valuable insights into the project's effects.

To contextualize these results, Table 1 presents a summary of the participants' demographic characteristics. The sample consists

primarily of women, with varying levels of education, marital status, and ethnic backgrounds. Given that many participants have limited formal education and come from communities where digital access is historically restricted, their baseline digital literacy levels, and gender attitudes provide critical reference points for understanding the intervention's impact.

### 4.2.1 Digital skills

Figure 1 presents the distribution of digital skills across four domains—Communication, Information, Problem-Solving, and Software—before and after the intervention. The bars represent the number of participants at different skill levels (none, low, basic, and above basic) at both time points, with blue indicating the pre-intervention period and green representing the post-intervention period.

A clear shift toward higher skill levels is observed across all four domains. Before the intervention, the majority of participants had no digital skills in all categories, as shown by the dominance of blue bars in the "none" category. However, after the intervention, there was a notable reduction in the number of participants with no skills and a corresponding increase in those achieving basic and above-basic skill levels.

Specifically for Communication and Information skills, before the intervention, nearly all participants lacked communication and information-related digital skills. After the intervention, a substantial proportion of participants progressed to above-basic levels, indicating an increased ability to use digital tools effectively for communication and information retrieval. For Problem-Solving and Software skills, a similar trend is evident in these domains, where post-intervention results show an increased number of participants attaining basic and above-basic competencies. This suggests that the training significantly improved their ability to navigate digital challenges and use software applications more effectively.

Table 2 presents the results of the Wilcoxon Signed-Rank Tests for digital skills, showing significant improvements across all assessed domains. The analysis reveals statistically significant changes in self-reported competencies before and after the intervention. Given the ordinal nature of the data, the Wilcoxon Signed-Rank Test was used to assess shifts in participants' skill levels across four categories: Information, Communication, Problem-Solving, and Software. The results indicate highly significant improvements in all domains ($p < 0.001$), suggesting that the training was associated with substantial gains in digital literacy.

The median scores for all four skills increased notably—each moving from a pre-intervention median of 1 (none) to a post-intervention median of at least 3 (basic) or 4 (above basic). This upward shift suggests that participants not only acquired basic competencies but also gained sufficient confidence to perform more advanced tasks, such as evaluating online information

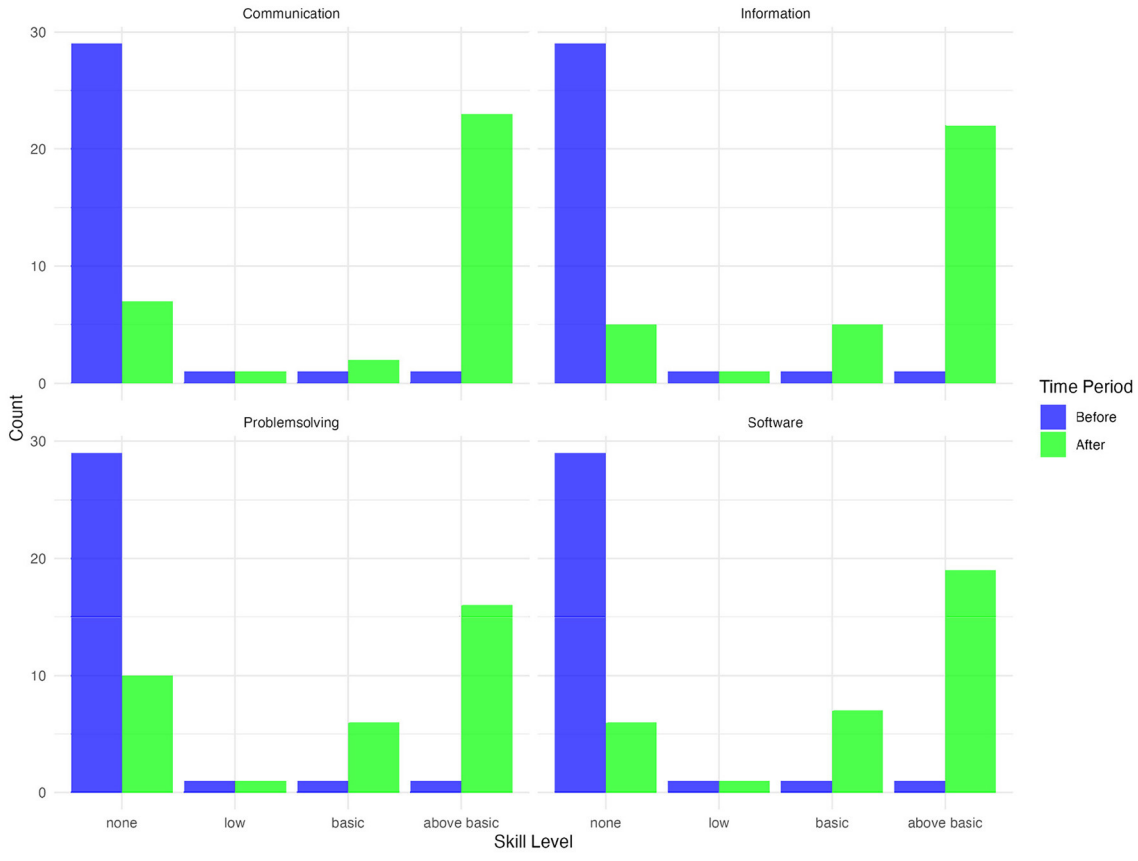


FIGURE 1
Digital skills by level before and after intervention. Source: Authors' own calculations, 2023.

TABLE 2 Wilcoxon Signed-Rank Test results for digital skills.

| Digital skill | *n* (paired) | Median before | Median after | Wilcoxon V | p-value | Effect size (*r*) |
|---|---|---|---|---|---|---|
| Information | 29 | 1 | 4 | 0 | 4.28e−06*** | 0.881 |
| Communication | 29 | 1 | 4 | 0 | 4.61e−06*** | 0.864 |
| Problem-solving | 29 | 1 | 3 | 0 | 4.52e−05*** | 0.808 |
| Software | 29 | 1 | 4 | 0 | 1.06e−05*** | 0.857 |

*p < 0.05, **p < 0.01, ***p < 0.001. Source: Authors' own calculations, 2023.

and navigating diverse software tools. These differences were statistically significant, as evidenced by the small *p-values* and substantial effect sizes (e.g., $r = 0.81–0.88$). Such high effect sizes underscore the practical importance of these changes, implying that the training meaningfully enhanced participants' digital literacy across all skill domains.

These results indicate that the intervention had a statistically significant impact on enhancing digital competencies across all skill areas. The findings suggest that participants not only gained foundational digital skills but also advanced their abilities to navigate and engage with technology in more complex ways. These results underscore the effectiveness of the training in bridging digital gaps and promoting digital inclusion among the participants.

### 4.2.2 GEM scale

The analysis of the GEM scale provides insights into how participants' attitudes toward gender-equitable norms, particularly in areas related to gender roles, violence, and masculinity, changed following the intervention. The training on positive masculinities aimed to encourage reflection on traditional beliefs, and the results presented in Figure 2 indicate notable shifts in responses.

One of the most apparent changes was observed in attitudes toward gender roles. Before the intervention, a substantial proportion of respondents expressed agreement with statements reinforcing traditional expectations, such as "The most important role of a woman is to take care of her home and cook for her family" and "Changing diapers, bathing, and feeding the children is the mother's responsibility." Following the intervention, there was an increase in the number of respondents who "Totally disagree" with these statements, suggesting a movement away from rigid, gender-based domestic roles. This shift may indicate a greater openness to more flexible understandings of caregiving responsibilities.

Changes were also observed in attitudes toward violence and masculinity. Prior to the training, a considerable number of participants agreed with statements such as "A woman should tolerate her partner's violence to keep her family together" and "To be a man, you have to be strong." After the intervention, a higher proportion of respondents "Totally disagreed" with these statements, suggesting a shift in perspectives regarding the acceptability of violence and traditional notions of masculinity centered on strength and dominance. While these changes in responses indicate a rejection of certain traditional norms, further research would be needed to assess whether these shifts reflect longer-term attitudinal change.

The broader trends in response distributions, suggest an overall movement toward more progressive attitudes post-intervention. While individual perspectives on gender roles and masculinity are shaped by multiple factors and may not change immediately, the observed shifts in responses provide preliminary evidence that participants engaged with the themes presented in the training and may have reconsidered certain traditional norms. These findings highlight the potential of targeted training programs to facilitate discussions about gender roles and masculinity in contexts where these norms are deeply embedded, for more information see Supplementary Figure A1.

The analysis of the GEM scale, presented in Figure 3, analyzes the average change in attitudes toward gender-equitable norms across demographic groups. Although the confidence intervals indicate that these differences are not statistically significant, they suggest areas for further exploration. Specifically, men exhibited slightly greater shifts in GEM scores compared to women, particularly in attitudes related to masculinity and caregiving. Education level also appeared to influence responses, with those having some or completed elementary education showing the highest positive changes, though the differences were not statistically strong. Notably, the bar for individuals with Middle School education is missing in the figure because no respondent of the GEM survey reported that level of education. Marital and parental status played a minor role, with married individuals and parents demonstrating slightly higher shifts, possibly reflecting their engagement in household dynamics.

Table 3 presents the Wilcoxon p-values for the GEM scale items, offering insights into changes in attitudes toward gender roles, masculinity, and violence following the intervention. The response categories for these items are ordinal, where a score of 1 indicates total agreement with the statement, 2 indicates partial agreement, and 3 indicates disagreement. Given the ordinal nature of the response categories, the Wilcoxon Signed-Rank Test was used to assess whether these changes were statistically significant. This non-parametric test was chosen because it is appropriate for paired data when comparing pre- and post-intervention responses without assuming a normal distribution. The results indicate that several items showed statistically significant shifts, suggesting a potential influence of the training on participants' views.

The median values on several items moved higher (e.g., from 2 to 3 or from 1 to 2), signifying decreasing agreement with traditional statements about women's roles, men's decision-making power, and the acceptability of violence. For example, the statement *"Man should have the final say about decisions in his home"* ("Men Have the Last Word") showed no change in the median score (remaining at 3), yet the Wilcoxon test indicated a statistically

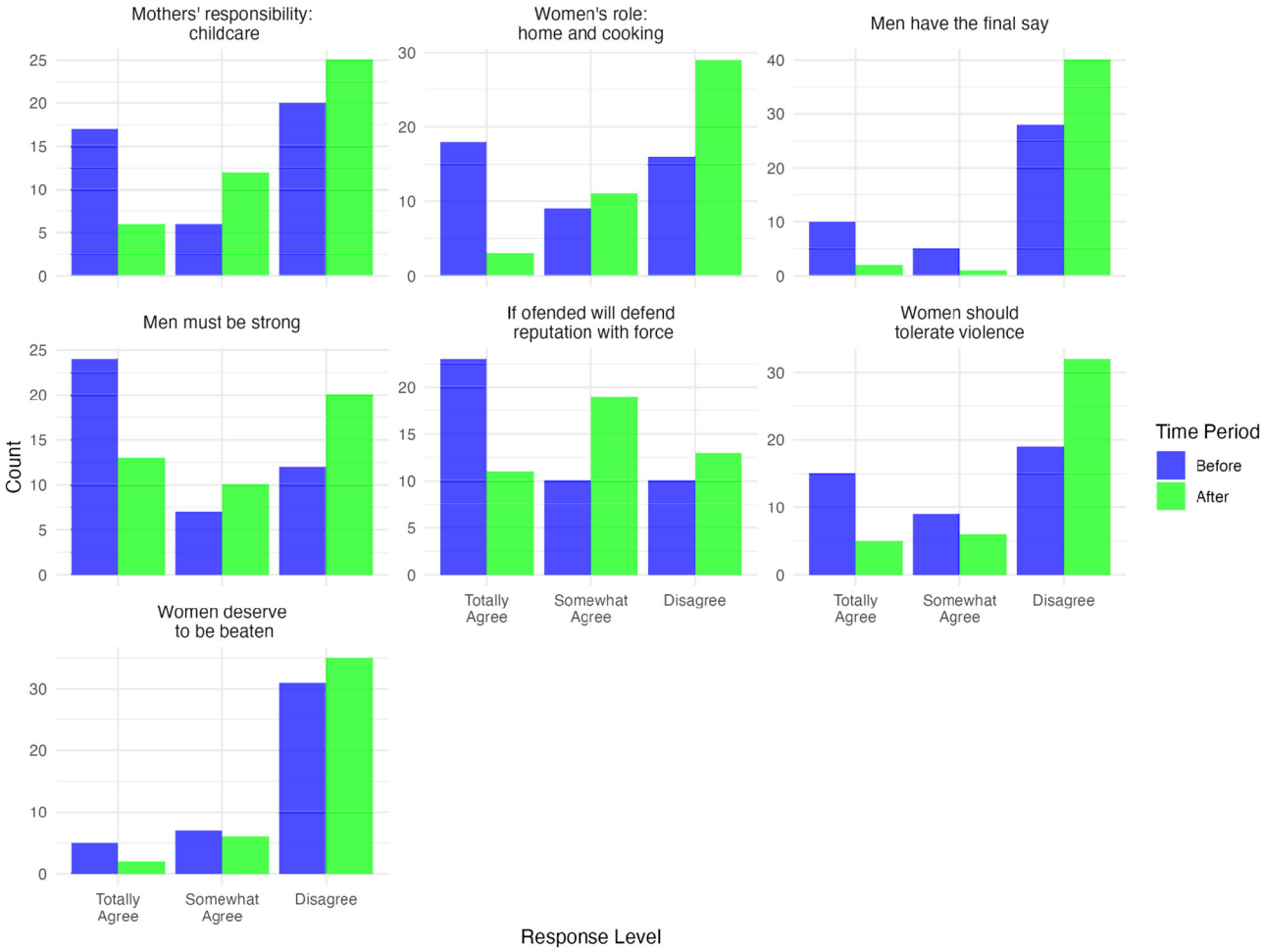


FIGURE 2
Number of responses for GEM scale before and after intervention. Source: Authors' own calculations, 2023.

significant shift in the distribution of responses ($V = 11.0$, $r = 0.503$). This suggests that while the central tendency did not shift, many participants adjusted their responses in a more egalitarian direction, potentially moving from stronger to more moderate agreement or toward disagreement. The statement *"Most important role for a woman is to take care of her home and cook for her family"* ("Cook & Home") showed a marked increase in median (from 2 to 3), reflecting more equitable views on domestic responsibilities. The Wilcoxon V values for these items were relatively high, suggesting that the observed changes were not only statistically significant but also broadly shared across participants. Furthermore, the effect sizes ranged from moderate to large (e.g., $r = 0.38 - 0.52$), reinforcing the conclusion that the intervention had a meaningful impact on reshaping these gender-related attitudes.

Although most items showed significant changes, a few did not. The statement *"There are times when a woman deserves to be beaten"* ("Women Beaten") did not pass the significance threshold, indicating that while some participants shifted their views on this topic, the change was not as pervasive as for other items. Similarly, the statement *"If someone insults me, I will defend my reputation, even by force if necessary"* ("Reputation") failed to reach statistical significance, suggesting that reducing the importance placed on men's public image may require additional time or more targeted interventions.

The Wilcoxon Signed-Rank Test detects changes in the distribution of responses but does not establish causality. The observed patterns may suggest an association between the intervention and changes in views on masculinity, domestic roles, and the acceptability of violence. However, some items did not show significant movement. These findings underscore the potential of targeted interventions to foster more equitable attitudes, particularly in areas where initial views were more traditional. Future research should explore whether these shifts are sustained over time and whether they correspond with changes in behavior at the household or community level.

### 4.2.3 GNDR-4 scale

The results from the GNDR-4 scale analysis reveal significant shifts in attitudes toward gender equality following the intervention on positive masculinities. The training aimed to challenge

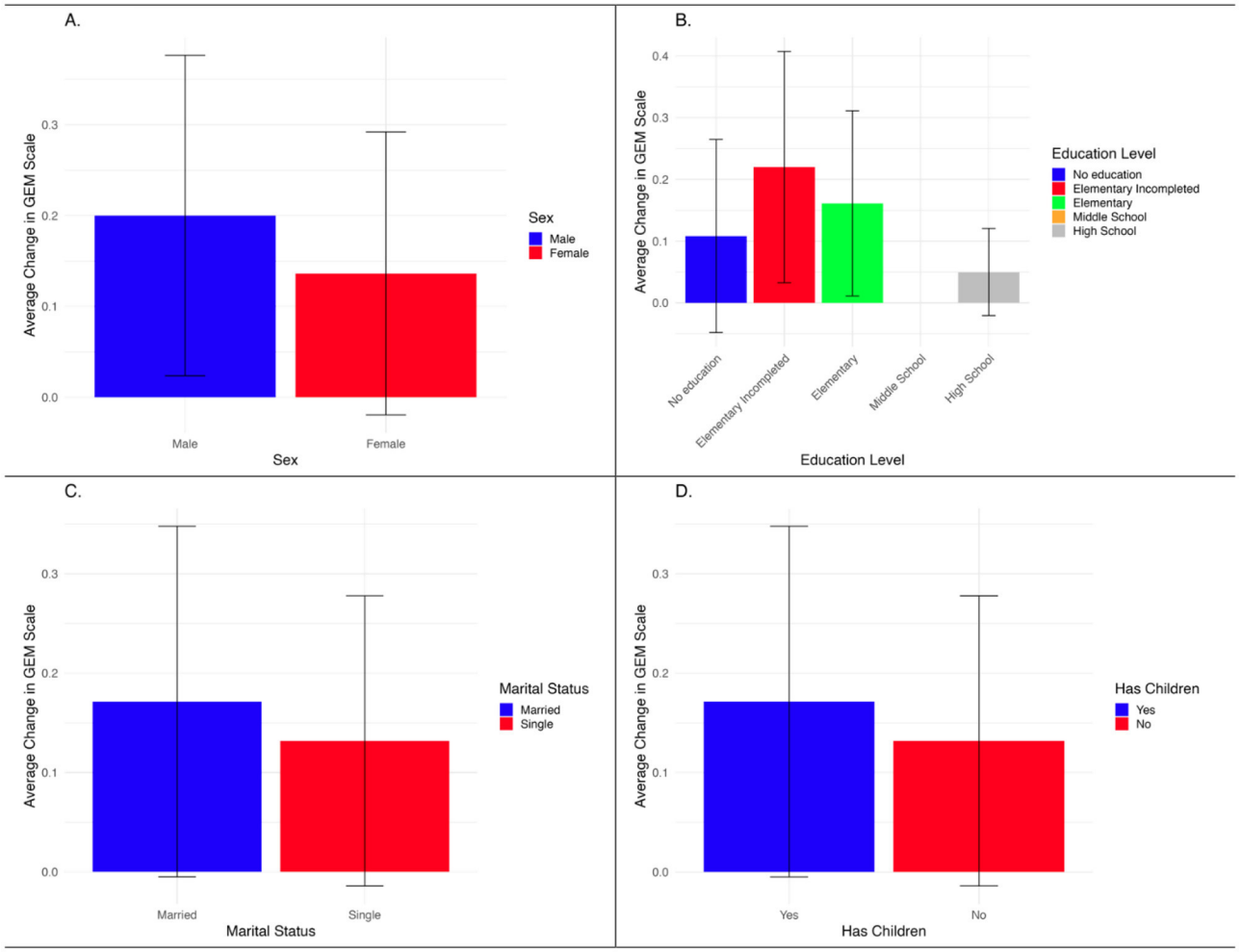


FIGURE 3
Average change GEM scale by demographic variables. Source: Authors' own calculations, 2023. **(A)** Sex. **(B)** Education level. **(C)** Marital status. **(D)** Has children.

traditional gender norms and promote more equitable perspectives. The findings, illustrated in Figure 4, show meaningful changes in respondents' views regarding women's rights, economic opportunities, and political leadership.

Before the intervention, the majority of respondents either "Agreed" or "Totally agreed" with the statement that women should have equal rights as men. However, post-intervention, there was a noticeable increase in the number of respondents who "Totally agree," signaling a stronger endorsement of gender equality. A similar trend is observed in responses to the statement "Men should get jobs first when scarce." While a significant proportion of participants initially supported or were neutral on this notion, post-intervention responses showed a marked increase in the "Totally disagree" category, indicating a rejection of the idea that men should be prioritized over women in employment during times of scarcity. This shift suggests that the training successfully challenged deep-rooted economic biases that favor men in the workforce.

A related change occurred in attitudes toward political leadership. Prior to the intervention, responses to the statement "Men are better political leaders than women" were mixed, with a considerable number of respondents expressing agreement. However, post-intervention, there was a clear increase in those who "Totally disagree," reflecting a growing rejection of the belief that men are inherently better suited for leadership roles. This shift suggests that the training not only influenced participants' views on economic equality but also challenged traditional notions of political representation and leadership.

These changes in attitudes are further illustrated by the overall distribution of responses on the GNDR-4 scale. As shown in Supplementary Figure A2, the density distribution reveals a notable shift from before to after the intervention. Prior to the intervention, responses were highly concentrated in the lower range of the scale (around 8–10 points), suggesting relatively low endorsement of gender-equitable norms. After the intervention, the distribution flattened and extended further toward higher values, indicating greater variability and a general movement toward more progressive attitudes. This post-intervention shift implies that participants, on average, endorsed more gender-equitable views after exposure to the training. While the earlier distribution sharply peaked, the broader spread in the after group

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TABLE 3 Wilcoxon Signed-Rank Test results for GEM items.

| GEM item | *n* (paired) | Median before | Median after | Wilcoxon V | p-value | Effect size (*r*) |
|---|---|---|---|---|---|---|
| Cook and home | 43 | 2 | 3 | 51.0 | 0.00066*** | 0.523 |
| Children's responsibility | 43 | 2 | 3 | 108.5 | 0.04690* | 0.322 |
| Men have last word | 43 | 3 | 3 | 11.0 | 0.00444** | 0.503 |
| Tolerate violence | 43 | 2 | 3 | 28.5 | 0.00195** | 0.502 |
| Women beaten | 43 | 3 | 3 | 15.0 | 0.09730 | 0.237 |
| Men must be strong | 43 | 1 | 2 | 82.0 | 0.01470* | 0.375 |
| Reputation | 43 | 1 | 2 | 122.0 | 0.05580 | 0.326 |

*p < 0.05, **p < 0.01, ***p < 0.001. Source: Authors' own calculations, 2023.

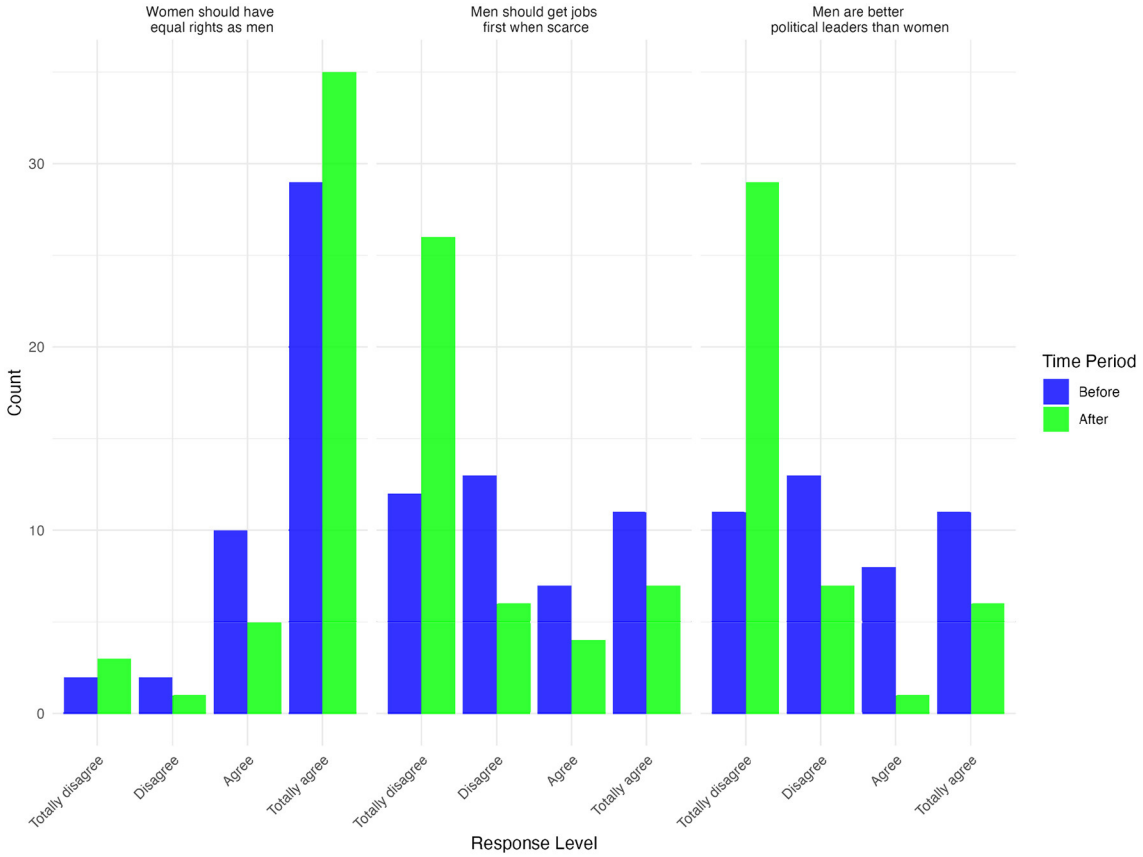


FIGURE 4
Number of responses for GNDR-4 scale before and after intervention. Source: Authors' own calculations, 2023.

suggests a more widespread uptake of non-traditional gender norms across participants.

Taken together, these findings suggest that the intervention was effective in fostering more egalitarian gender perspectives, particularly in areas related to economic participation and political leadership. While further research is needed to assess the long-term sustainability of these attitude changes, the results highlight the potential of targeted training programs in shifting deeply ingrained societal norms.

The analysis of the GNDR-4 scale by demographic variables, shown in Figure 5, displays the average change in attitudes across sex, education level, and marital status. While trends suggest that women, individuals with higher education, and single participants exhibited more progressive views post-intervention, the confidence intervals indicate that these differences are not statistically significant. The lack of statistical significance suggests that the observed variations may be due to sample variability rather than the intervention's direct impact. Notably, the "Middle School" education group includes only one respondent, which prevents calculation of a standard deviation and thus results in the absence of an error bar for that category. These findings highlight the need for further research with a larger and more balanced sample to

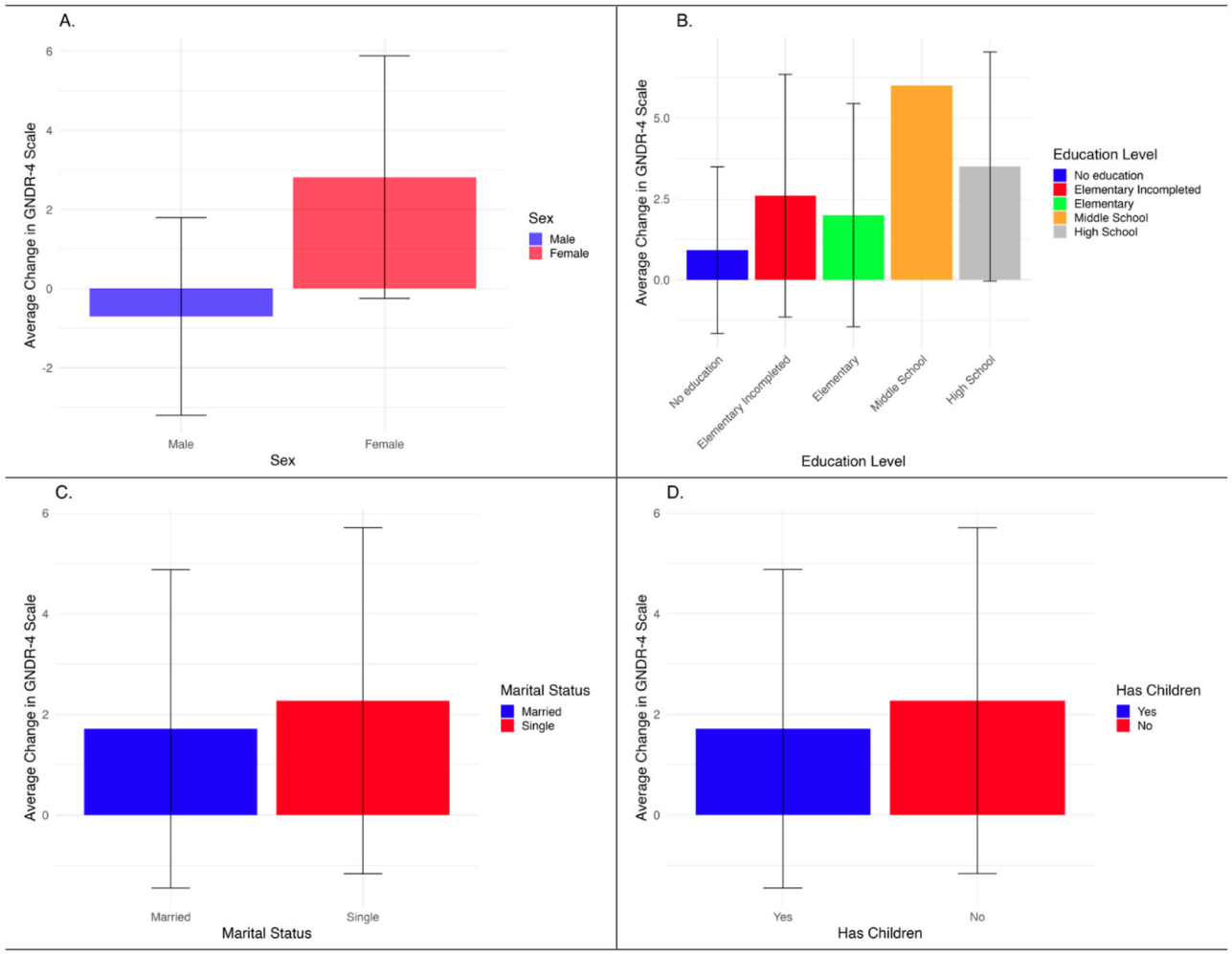


FIGURE 5
Average change GNDR-4 scale by demographic variable. Source: Authors' own calculations, 2023. **(A)** Sex. **(B)** Education level. **(C)** Marital status. **(D)** Has children.

determine whether the intervention effectively influences gender equality attitudes across different demographic groups.

To assess whether the intervention led to significant changes in attitudes toward gender equality, we conducted Wilcoxon Signed-Rank Tests on the GNDR-4 scale items. This test was chosen because it is suitable for ordinal Likert-scale data and evaluates whether the distribution of responses before and after the intervention significantly differs. Unlike parametric tests, Wilcoxon does not assume a normal distribution, making it an appropriate choice for non-normally distributed ordinal data.

Table 4 presents the results of the Wilcoxon Signed-Rank Test for each of the GNDR-4 items, measuring shifts in attitudes toward gender equality before and after the intervention. The analysis reveals statistically significant changes in two out of the three items, particularly in attitudes toward political leadership and labor rights. The original response scale ranged from −2 to 2, where −2 indicates totally disagree, −1 disagree, 1 agree, and 2 totally agree. However, two items—*"Men are better political leaders than women"* and *"Men should get jobs first when scarce"*—were reverse-coded prior to analysis to ensure consistent interpretation across items. Specifically, responses were recoded so that higher values reflect greater disagreement with gender-inequitable statements (e.g., −2 became 2, −1 became 1, 1 became −1, and 2 became −2).

The most pronounced shift was observed in the item on political leadership ("Men are better political leaders than women"). Responses moved from a median of −1 (agree) to −2 (totally agree) on the reverse-coded scale, indicating increased disagreement with this traditional gender norm. The change was statistically significant ($p = 0.00087$) with a large effect size ($r = 0.521$), suggesting that participants became more supportive of women's leadership following the intervention. Attitudes regarding labor rights ("Men should get jobs first when scarce") also shifted significantly ($p = 0.0192$), with the median moving from −1 to −2, and a moderate effect size ($r = 0.322$). This suggests a meaningful reduction in agreement with the idea that men should be prioritized in employment during scarcity. In contrast, there was no statistically significant change in the item on equal rights ("Women should have equal rights as men"), with both the pre- and post-intervention median remaining at 2 (totally disagree on the reverse-coded scale). The non-significant *p-value* ($p = 0.297$)

TABLE 4 Wilcoxon Signed-Rank Test results for GNDR-4 items.

| GNDR-4 item | *n* (paired) | Median before | Median after | Wilcoxon V | p-value | Effect size (*r*) |
|---|---|---|---|---|---|---|
| Equal rights | 43 | 2 | 2 | 78.0 | 0.297000 | 0.194 |
| Political leadership | 43 | −1 | −2 | 392.5 | 0.000867*** | 0.521 |
| Labor rights | 43 | −1 | −2 | 249.0 | 0.019200* | 0.322 |

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Source: Authors' own calculations, 2023.

and small effect size ($r = 0.194$) suggest that participants already held strong egalitarian views on this issue prior to the intervention, leaving limited room for further improvement.

Since two of the three *p-values* are below the conventional 0.05 threshold, the results suggest that the observed changes in responses are unlikely to be due to random variation alone. The findings indicate that the intervention may be associated with shifts in attitudes toward gender equality, particularly in relation to political leadership and labor rights. While general support for equal rights remained high both before and after the intervention, significant changes in more specific beliefs—such as the idea that men are better political leaders or should be prioritized in employment—point to the potential influence of the training on participants' perspectives. However, these findings should be interpreted with caution, as the data do not allow for definitive causal conclusions. Further research, ideally with larger samples and longer follow-up periods, is needed to assess the durability of these attitudinal changes and their implications for behavior in real-world settings.

## 5 Discussion

The findings from this study highlight significant positive outcomes in the GNDR-4 and GEM scales, and Digital Skills tests following the intervention through the Digital Community Centers. These results are essential in understanding the multidimensional aspects of women's empowerment in rural Guatemala.

The intervention led to substantial improvements in digital competencies, with participants showing marked progress in communication, information, problem-solving, and software skills. These enhancements in digital literacy are significant, as they contribute to increased access to information, economic opportunities, and a sense of autonomy among the participants. This suggests that the digital skills training positively influenced women's empowerment in public and economic spheres.

The GEM scale, which focuses on social norms and attitudes, showed positive and significant changes in gender-equitable norms. The GNDR-4 scale, which measures attitudes toward gender equality in rights, economic positions, and political leadership, also saw significant positive and significant shifts. The intervention effectively challenged traditional gender roles and attitudes toward violence and masculinity, indicating a shift toward more progressive views. These findings align with previous research (Heeks and Molla, 2009), which underscores the transformative potential of digital skills for women's economic participation and advocacy.

A key contribution of this study is its extension of the ongoing discourse on the relationship between education, particularly digital education, and women's empowerment. Despite the positive outcomes previously discussed, the study did not find a statistically significant association between changes in digital skills and the GNDR-4 and GEM scales. This lack of statistical significance may be attributed to the small sample size, which could have reduced the power to detect meaningful relationships. Moreover, the high levels of rurality and lower development in the study area might hinder the translation of digital literacy into measurable changes in women's empowerment (Heeks, 2010). These findings suggest that while digital education holds promise, its impact on women's empowerment requires further investigation with larger sample sizes and more rigorous methodologies, such as randomized controlled trials (RCTs).

Another contribution of this paper is the mixed-methods approach, which is particularly valuable in development projects conducted in challenging contexts (Bamberger et al., 2010). By employing a mixed-methods approach that integrates qualitative insights from focus groups with quantitative data from the GNDR-4, GEM scales, and digital skills assessments, this study provides a more nuanced view of how Digital Community Centers (DCCs) advance women's empowerment. While the quantitative results highlight significant gains in digital skills and shifts toward more equitable gender norms, the qualitative data offer valuable context, revealing that local leadership structures—particularly Women's Leadership Committees—can amplify these benefits by mobilizing resources and strengthening ties with community authorities. Male buy-in to positive masculinities, however, appears to vary by factors such as age and educational background, underscoring the need for tailored approaches to sustain attitudinal changes.

The regression results, provided in the Supplementary Table A1, are not statistically significant, and the direction of the associations between digital education and women's empowerment varies depending on the survey. Increased digital education appeared to positively influence empowerment in terms of rights, economic status, and political leadership (as measured by GNDR-4). Conversely, it seemed to have a negative relationship with gender norms in the private sphere (as measured by GEM). This contrast suggests that while digital education may empower women in public and economic domains, it could also challenge traditional gender norms in private spheres, leading to resistance or slower changes. These findings align with the literature, which indicates that different dimensions of women's empowerment can respond differently to similar interventions (Kabeer, 1999; Qian and Li, 2020).

In addition to illustrating the DCCs' direct benefits—such as reducing travel time and enhancing digital literacy—this

mixed-methods design underscores the broader, structural elements crucial to making these transformations durable. Although DCCs clearly improve women's daily tasks, broader policy support remains essential to solidify and expand these gains. Infrastructure upgrades, mentorship programs, and ongoing financial backing all emerge as critical pathways for turning the centers into lasting community anchors. By combining robust statistical evidence with in-depth qualitative narratives, the mixed-methods approach captures both the measurable outcomes of digital interventions and the lived realities that influence how—and for whom—empowerment takes shape.

Another major contribution of this study is its focus on Mayan women in rural and remote areas of Northern Huehuetenango, Guatemala—a population that has been largely understudied. This focus provides valuable insights into the specific challenges and opportunities for digital literacy and empowerment within this unique cultural and geographical context. To gain a deeper understanding of these dynamics, future research should explore the impact of digital literacy on women's empowerment with larger and more diverse samples. Conducting RCTs could yield more definitive evidence on the associations between digital education and various aspects of women's empowerment. Additionally, understanding the contextual factors that influence these outcomes, such as cultural resistance and socioeconomic conditions, will be critical for designing more effective interventions (Hafkin and Odame, 2002).

In conclusion, Digital Community Centers and digital training play a critical role in bridging the digital divide and promoting gender equality in rural Guatemala. By providing access to digital technologies and training, DCCs empower indigenous women, fostering economic, and social development. While the study underscores the positive impacts of DCCs, it also highlights the need for continuous and inclusive efforts to address gender disparities. Future interventions should build on these findings, ensuring that digital inclusion strategies are comprehensive, culturally sensitive, and sustainable. Women reported increased confidence in digital literacy and leadership skills, which translated into greater participation in decision-making processes within their communities. The focus groups emphasized the importance of community collaboration and support, as both men and women recognized the value of gender equality and shared leadership roles. Participants also noted the reduction in gender-based barriers and a shift toward more equitable social norms, fostering a more inclusive and supportive community environment.

## 6 Challenges and limitations

While this study provides valuable insights into the impact of Digital Community Centers (DCCs) on indigenous women in Northern Huehuetenango, the small sample size, particularly in the quantitative analysis, limits the generalizability of our findings. The remote nature of the study area and logistical challenges constrained our ability to gather a larger dataset. Future research should consider employing larger sample sizes or randomized controlled trials to validate these initial findings and further explore the relationship between digital literacy and gender empowerment in similar contexts. Expanding the study to include other regions or communities would also help to establish the broader applicability of the results.

Our analysis revealed that the association between changes in digital literacy and gender empowerment, as measured by the GEM scale, was not statistically significant. This lack of statistical significance suggests that the relationship between these variables may be more complex than initially hypothesized. Several factors, such as cultural resistance to changing gender norms or the limitations of the survey instruments in capturing subtle shifts in empowerment, could have influenced these results. Future studies should explore these non-significant findings in greater depth, potentially incorporating additional variables or alternative methodological approaches to better understand the dynamics at play.

Policymakers should prioritize digital inclusion as a cornerstone of rural development agendas, recognizing the multifaceted role that Digital Community Centers can play in empowering marginalized populations. To ensure the sustainability and effectiveness of these initiatives, it is crucial to allocate sufficient resources for infrastructure, training, and ongoing community engagement. Moreover, digital literacy programs should be designed with cultural sensitivity and tailored to address the specific needs of indigenous communities, incorporating feedback mechanisms to adapt to evolving challenges.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants.

## Author contributions

NYOO: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Data curation, Methodology, Resources, Software, Validation, Visualization. SA: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Supervision. AA: Data curation, Supervision, Writing – original draft.

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## Conflict of interest

The authors of this study declare that there are potential conflicts of interest, as some of them are employed by New Sun Road, P.B.C., and New Sun Road Guatemala, S.A., the entities responsible for implementing the Digital Community Centers (DCCs) evaluated in this project. This affiliation could be perceived as an influence on the interpretation of the results and conclusions of the study. To mitigate any potential conflicts of interest, the authors have taken measures to ensure transparency and objectivity in the research process, including data review and analysis by third parties with no direct affiliation with New Sun Road. Additionally, strict ethical procedures have been followed, and the well-being of the participants has been prioritized in all phases of the study. By transparently addressing these potential conflicts of interest, we aim to maintain the integrity and credibility of our findings.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frma.2025.1488916/full#supplementary-material

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