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## QUALITY OF LIFE, DEVELOPMENT AND SOCIAL RESPONSIBILITY, CLIMATE CHANGE AND THE ENVIRONMENT

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*The Editorial Board would like to express its deep gratitude to the peer reviewers who contributed their time and expertise to ensure the scientific quality of the articles published in this issue.*

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# *Editorial*

Dear reader,

The special issue of *La Granja: Revista de Ciencias de la Vida*, Vol. 43 No. 1 (March 2026), entitled "Quality of Life, Development and Social Responsibility, Climate Change and the Environment," stands as a significant contribution to the scientific and ethical analysis of the challenges confronting contemporary sustantability. La Granja, ranked among the top ten journals with the greatest relevance in publishing research related to sustainability, reaffirms its commitment to the generation and dissemination of rigorous knowledge that addresses the environmental, social, and economic challenges of our time and region.

In a world facing profound inequalities and global environmental crises, science bears the responsibility of guiding the future toward climate justice, social equity, and the preservation of life in all its forms. Accordingly, this issue addresses environmental and social approaches from diverse research perspectives, underscoring the need to integrate scientific knowledge with civic responsibility and political action.

The published articles examine urgent issues such as ecosystem degradation, sustainable productive transformations, climate change adaptation, and green technological innovation. At the same time, they emphasize central themes of social responsibility and quality of life, recognizing that human well-being cannot be separated from ecosystem health, nor from respect for cultural and biological diversity. In this regard, sustainability, as presented by the authors of this issue, is not conceived as an abstract concept but rather as a transformative practice that must be incorporated into education, public policy, business management, and everyday life.

This special issue includes valuable research ranging from macro-level analyses of regional transformations to studies of local productive systems across diverse approaches and territories. From a holistic perspective encompassing environment, society, and culture, Mayel Camila Castillo Ruge, Lina Paola Alfonso Chaparro, Daniel Alejandro Valderrama, and Néstor Adolfo Pachón Barbosa, from the Universidad Pedagógica y Tecnológica de Colombia, present in their article "Environmental Transformations in Latin America" a critical review of sustainable practices across territories. They analyze these practices and highlight the need to consider them as culturally embedded challenges, thereby rethinking development models through inclusive, intercultural, and ecological approaches.


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Based on an analysis of the effectiveness of the Northeast Arid Zone Development Program (NEAZDP) as a poverty mitigation strategy implemented in Yobe State, Nigeria, in 2023, researchers Mohammed Sanusi Sadiq and Isiyaku Jawa Grema from the Federal University Dutse (FUD) demonstrate how the program reduced both unidimensional and multidimensional poverty, particularly across three pillars associated with quality of life: access to education, healthcare, and income generation. They conclude that sustaining its long-term impact requires continuous and targeted interventions integrated into public policies oriented toward poverty alleviation and inclusive development.

In the context of household-level water scarcity, user behavior in drinking water services is crucial for ensuring quality of life. In this regard, Jessica Müller-Pérez from the Universidad Popular Autónoma de Puebla, Ángel Acevedo-Duque from the Universidad Autónoma de Chile, Montserrat Sánchez Espinosa from the Universidad Popular Autónoma de Puebla, Irma Yomara Verges from the Universidad Autónoma de Chile, and Rina María Álvarez-Becerra from the Universidad Nacional Jorge Basadre Grohmann, in their article "Construction of an Instrument Based on the EGCI Model to Measure Sustainable Water-Use Practices among Citizens," determined citizens' intention to adopt sustainable water-care practices. Applying a model grounded in consumption economics that articulates four critical dimensions—Sustainable Water Management, Moral Commitment, and Intention to Adopt Sustainable Practices (EGCI)—they demonstrate that moral commitment and water-saving behavior significantly influence population behavior. They emphasize the need to promote environmental education focused on sustainable water management and to design strategies aimed at reducing waste and increasing efficiency in residential water use, particularly in territories where this natural resource is being depleted at alarming rates.

Quality of life is also closely linked to the health of rural socioecological systems, especially those sustaining food security. Research conducted in Colombia, in Cundinamarca (municipalities of Cáqueza, Choachí, and Fómeque) and Boyacá (municipalities of Sutamarchán, Santa Sofía, Sáchica, Tinjacá, and Villa de Leyva), by the research team led by Karla Juliana Rodríguez-Robayo, Víctor Camilo Pulido-Blanco, Carlos Andrés Moreno-Velandia, Diego Alejandro Rojas-Ramírez, Eduardo María Espitia-Malagón, Mauricio Camelo-Rusinque, Andrea del Pilar Villarreal-Navarrete, and Yajaira Romero-Barrera from the Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA), identified critical points within the social, environmental, productive, and governance components of the tomato socioecological system. These components are determinant for promoting transitions toward sustainable production models, given their importance in providing ecosystem services essential to production and to the quality of life of producers and, consequently, consumers.

Taken together, the scientific articles compiled in this special issue confirm that addressing quality of life requires a multi- and transdisciplinary approach. Culture, technology, and the social and environmental context shape practices that may enhance or deteriorate the quality of life of populations, particularly rural communities. We are confident that these academic contributions will provide guidance for the development of targeted actions and emerging public policies aimed at sustainable development and the improvement of quality of life in both urban and rural populations.

Within our selection of miscellaneous articles in the Earth Sciences, we present the article "Meteorological Variability and Its Impact on Agricultural Activities in the Ecuadorian Amazon in Pastaza (2011–2021)," authored by Brigitte Leiva-Zuñiga, Julia Maza-Valladolid, and Reni Vinocunga-Pillajo from the Faculty of Life Sciences at Universidad Estatal Amazónica (Puyo, Ecuador). This study analyzes the relationship between meteorological variables—temperature, precipitation, relative humidity, and evaporation—and agricultural and livestock productivity in the canton of Pastaza over a decade. The research provides key scientific evidence regarding the differential vulnerability of strategic crops such as cocoa, coffee, and sugarcane to climate variability, highlighting the greater resilience of plantain and cassava.

Similarly, the manuscript "Quantitative Analysis of Crop Richness and the Adoption of Monocultures in Ecuador" examines the socioeconomic determinants influencing agricultural diversification and the expansion of monoculture in the country, using data from the 2014 Living Conditions Survey and multivariate techniques. The study shows that poor, large households led by Indigenous populations tend to maintain greater crop richness, whereas factors such as higher education levels, off-farm employment, and proximity to roads promote monoculture adoption. In this way, the work contributes to a structural understanding of the transformation of rural productive systems under the pressures of the market economy. Its social impact is significant, as it underscores the need for public policies aimed at protecting agrobiodiversity as a strategy for environmental sustainability, food sovereignty, and the resilience of rural territories in Ecuador.

From the Agricultural Sciences, the study entitled "In Vitro Propagation of Banana (*Musa* spp.) through Somatic Embryogenesis," by Jessenia Lucero-Murillo, Jorge Manzano-Torres, Iliana Loaiza-Maldonado, and Yamile Orellana-García from the Instituto Superior Tecnológico Ismael Pérez Pazmiño (Machala, Ecuador), presents a systematic review of the use of somatic embryogenesis as a tool for micropropagation and genetic improvement of banana. The research analyzes the potential of this technique for mass plant multiplication and its application in genetic transformation processes aimed at combating devastating diseases such as *Fusarium oxysporum f. sp. cubense* (Foc TR4) and *Mycosphaerella fijiensis*. This study strengthens the field of plant biotechnology applied to strategic export crops, providing technological alternatives to sustain the competitiveness of the banana sector, which is fundamental to the regional economy and rural employment generation.

Likewise, the article "Effects of Lead and Chromium on Germination and Root Architecture of *Typha latifolia* (Typhaceae) Seedlings," developed by Renato Oquendo and Galo Pabón-Garcés from Universidad Técnica del Norte (Ibarra, Ecuador), Loiret Fernández from the Universidad de La Habana (Cuba), and Lucía Vásquez-Hernández, experimentally examines the impact of heavy metals on germination and root development in this aquatic species. The results demonstrate that chromium drastically reduces germination percentage and significantly affects root area, highlighting the importance of the physiological response of aquatic macrophytes to contamination. The study underscores the relevance of environmental management of water bodies and the need to strengthen heavy metal pollution control policies in strategic ecosystems such as Yahuarcocha Lagoon.

In the field of Biotechnology, the research entitled "Valorization of Banana Peel (*Musa paradisiaca*) as Raw Material for Biopolymer Production," by Jimena Taco, Ronald Jiménez, and María Soto from the Instituto Superior Tecnológico Tsáchila, investigates the development of biofilms derived from agroindustrial banana waste. The study evaluates physicochemical parameters such as viscosity, moisture absorption, and water vapor permeability under different processing conditions and glycerol concentrations, thereby contributing to the field of green chemistry and biomaterials engineering. The social impact of this research is particularly significant in the context of the global plastic pollution crisis, as it proposes sustainable alternatives that also promote circular economy principles and the valorization of agricultural waste.

Finally, the article "Optimization of Acid Hydrolysis Factors to Obtain Glucose from Banana, Cocoa, African Palm Residues and Sugarcane Bagasse," by Mónica F. Abril-González, Angélica M. Vele-Salto, and Verónica Pinos-Vélez from IRCMA and the Faculty of Chemical Sciences at the Universidad de Cuenca (Eco-Campus Balzay, Ecuador), experimentally optimizes the conditions to maximize glucose production from residual biomass using a factorial design. The authors identify 120 °C, 150 minutes, and 1 % sulfuric acid as optimal conditions, highlighting the high yield obtained from sugarcane bagasse and palm rachis. This research constitutes an additional contribution to the transition toward more sustainable energy matrices, the valorization of agroindustrial residues, and the reduction of fossil fuel dependency in Ecuador.

Within this context, the studies compiled herein underscore that both research processes and teaching–learning processes must be oriented toward the construction of values of respect, solidarity, and empathy toward the natural environment. From this perspective, quality of life is not limited to economic indicators but extends to equity in access to education, healthcare, environmental services, and collective participation in decision-making. This special issue invites reflection on how life sciences can and must transform into a science for life: an inclusive, ethical science capable of strengthening dialogue between technical knowledge and ancestral wisdom. The published studies reflect the journal's commitment to disseminating interdisciplinary results that contribute to the design of long-term sustainable policies. Collectively, the articles constitute a call for scientific cooperation and shared action in response to global challenges.

With this special issue, *La Granja: Revista de Ciencias de la Vida* reaffirms its commitment to the dissemination of responsible knowledge, the promotion of critical thinking, and the construction of a global culture of sustainability. We extend our gratitude to the researchers, reviewers, academic institutions, and readers who make possible this space for encounter and reflection, oriented toward the defense of the planet and the improvement of quality of life for all its inhabitants.

Sincerely,

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*Special Issue* / Edición Especial
Quality of life and sustainability



# Environmental transformations in Latin America, a critical review of the sustainable practices in the territories

# Transformaciones ambientales en América Latina, una revisión crítica de las prácticas sustentables en los territorios

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**Abstract**

Sustainable practices are a set of behavioral strategies aimed at satisfying human needs within a specific historical, cultural, and community framework, emphasizing the harmonious relationship with the natural environment, society, and culture. These practices are considered fundamental pillars in the promotion of sustainable behaviors in local, urban, rural, educational, and other communities, adopting a participatory approach for their implementation. In a context such as Latin America and the Caribbean, the need to incorporate sustainable practices arises from the environmental challenges generated by the historical processes of extractivist development dissociated from native cultures, making it necessary to rethink development models towards approaches that prioritize equity, ethics, and environmental justice. The study aims to identify research on the theoretical and procedural approach to sustainable practices in the LATAM context. A systematic review of 200 academic articles addressing the theoretical and procedural approaches to these practices in Latin America during the period 2010–2024 is carried out. The results, organized by year of publication, type of study, data collection methods, and study populations, reveal how sustainable practices have evolved and strengthened in diverse inclusive contexts, such as educational, peasant, and indigenous communities. This analysis provides a detailed overview of the current landscape of environmental sustainability, contributing significantly to academic knowledge and serving as a basis for future research and public policies aimed at fostering a cultural transformation towards a more equitable, just, and responsible community development with nature.

***Keywords***: Sustainability, Communities, Cultural, Latin America, Environmental.

**Resumen**

Las prácticas sustentables son un conjunto de estrategias conductuales dirigidas a satisfacer las necesidades humanas dentro de un marco histórico, cultural y comunitario específico, destacando la relación armoniosa con el entorno natural, la sociedad y la cultura. Estas prácticas se consideran como pilares fundamentales en la promoción de comportamientos sustentables en las comunidades locales, urbanas, campesinas, educativas y otras, adoptando un enfoque participativo para su implementación. En un contexto como LATAM y el Caribe, la necesidad de incorporar las prácticas sustentables surge de los desafíos ambientales generados por los procesos históricos del desarrollo extractivista y disociados de las culturas originarias, siendo necesario replantear los modelos de desarrollo hacia enfoques que prioricen la equidad, ética y justicia ambiental. El estudio tiene como objetivo identificar las investigaciones sobre el abordaje teórico y procedimental de las prácticas sustentables en el contexto latinoamericano. Se realiza una revisión sistemática de 200 artículos académicos que abordan los enfoques teóricos y procedimentales de estas prácticas en Latinoamérica durante el periodo 2010–2024. Los resultados, organizados por año de publicación, tipo de estudio, métodos de recolección de datos y poblaciones de estudio, revelan cómo las prácticas sustentables han evolucionado y se han fortalecido en diversos contextos integradores, como comunidades educativas, campesinas e indígenas. Este análisis proporciona una visión detallada del panorama actual de la sustentabilidad ambiental, contribuyendo significativamente al conocimiento académico y sirviendo de base para futuras investigaciones y políticas públicas orientadas a fomentar una transformación cultural hacia un desarrollo comunitario más equitativo, justo y responsable con la naturaleza.

***Palabras clave***: Sustentabilidad, Comunidades, Cultural, América Latina, Ambiental.

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# 1 Introduction

Throughout millions of years, human evolution has been a continuous process of adaptation and survival, from the Paleolithic era to the present day (Maya, 2015). In its early stages, humankind developed primitive tools that strengthened its relationship with nature (Carrillo, 2011). Nomadic societies, in their quest to satisfy basic needs, used natural resources and created communication methods that facilitated adaptation to their environment (Serrano, 2007).

With the end of the Paleolithic period came key transitions, particularly during the Neolithic era, when humans adopted agriculture and animal domestication, establishing sedentary and organized societies that laid the foundations for Food Sovereignty and Security (Leiva-Sajuria, 2014; Villalva and Inga, 2020). This advancement enabled social organization and the emergence of the first great civilizations. The Neolithic and Industrial Revolutions marked profound transformations in production, social organization, and the economy, establishing a model that continues to this day (Sanchís, 2013, citing Comín, 2011).

The Industrial Revolution caused a gradual rupture with nature and the past, replacing human energy with machines and giving rise to the modern economy (Valdivieso, 2009). However, this model is grounded in externalities and has imposed a hegemonic worldview that neglects local knowledge and sustainability, generating a systemic environmental crisis (Delgado and Rist, 2010; Porras and Pérez, 2018).

The current global scenario calls for a profound shift in human perception—from being mere managers of nature to recognizing ourselves as integral components of the environmental system (Mejía-Cáceres et al., 2018). This rethinking implies acknowledging that the current crisis is a consequence of modern culture, characterized by warfare and excessive industrialization, and thus requires a multidisciplinary re-evaluation (Noguera de Echeverri, 2011; Sarmiento and Larrinaga, 2021).

Among the proposals addressing this issue is Sustainable Development, conceptualized in the 1987 Brundtland Report as an alternative development model intended to reconcile tensions between environmental degradation and economic growth. However, it has failed to produce substantial changes regarding environmental challenges in most countries (Eschenhagen, 2015). Consequently, there is a growing need for a new paradigm such as *Sustentable* Development, which promotes development centered on sustainability through the integration of natural, social, and cultural relationships (Gómez, 2014; Carapia, 2022, citing Leff, 1998).

The Manifesto for Life, supported by Latin American scholars such as Enrique Leff, is an initiative led by UNEP within the framework of the Forum of Ministers of the Environment of Latin America and the Caribbean (Gudynas, 2014). It advocates for an ethic of Environmental Sustainability (ES) focused on a new social, local, and productive rationality (Coarasa and Pequeño, 2006). This approach seeks to maintain balance between the use of natural resources and the preservation of ecosystems (Sarmiento and Larrinaga, 2021), promoting practices and policies that ensure biodiversity conservation and the inclusion of communities marginalized by corporate discourses. Therefore, the environmental crisis in Latin America and the Caribbean demands the deconstruction of modern rationality and the adoption of a biocentric perspective (Leff, 2004).

In Latin America, paradigms such as environmental rationality, *Buen Vivir*, *Sumak Kawsay*, and Human-Scale Development propose an ES founded on the dialogue between community knowledge and local development. Within this framework, Sustainable Practices (SP) constitute the fabric of environmental sustainability, aiming to meet present needs without compromising those of future generations (Sandoval-Escobar, 2012), while valuing local behaviors and self-reliance (Valenzuela-Van Treek et al., 2021).

The objective of this study is to identify research on Sustainable Practices in Latin America (LATAM) between 2010 and 2024, contributing academically to new ways of understanding Environmental Sustainability in the Latin American and Caribbean context by highlighting alternative development approaches and ongoing research processes.

## 2 Materials and Methods

The methodological parameters guiding the development of this research are based on an integral, holistic, qualitative, and descriptive perspective of Environmental Sustainability (ES) and Sustainable Practices (SP) within Latin American contexts. Therefore, a descriptive scope was established, aiming to gather individual or collective information on conceptual and dissemination aspects. As inferred by Hernández and Mendoza (2018), descriptive studies "measure or collect data and report information on various concepts, variables, aspects, dimensions, or components of the phenomenon or problem under investigation" (p. 603).

Accordingly, this study adopted an integrative and descriptive methodology focused on a systematic review of academic articles related to SP and ES in Latin America (LATAM). The search and selection of documents were conducted through databases such as Google Scholar, Redalyc, SciELO, and Dialnet, using keywords including "prácticas sustentables", "sustentabilidad ambiental", and "América Latina", covering the period from 2010 to 2024.

The inclusion criteria considered articles originating from Latin American countries, published in Spanish, English, or Portuguese, and studies that explicitly addressed the topic in their title, abstract, or keywords. The exclusion criteria involved the removal of duplicates and studies not focused on ES. The search and selection process of the information is illustrated in Figure 1.

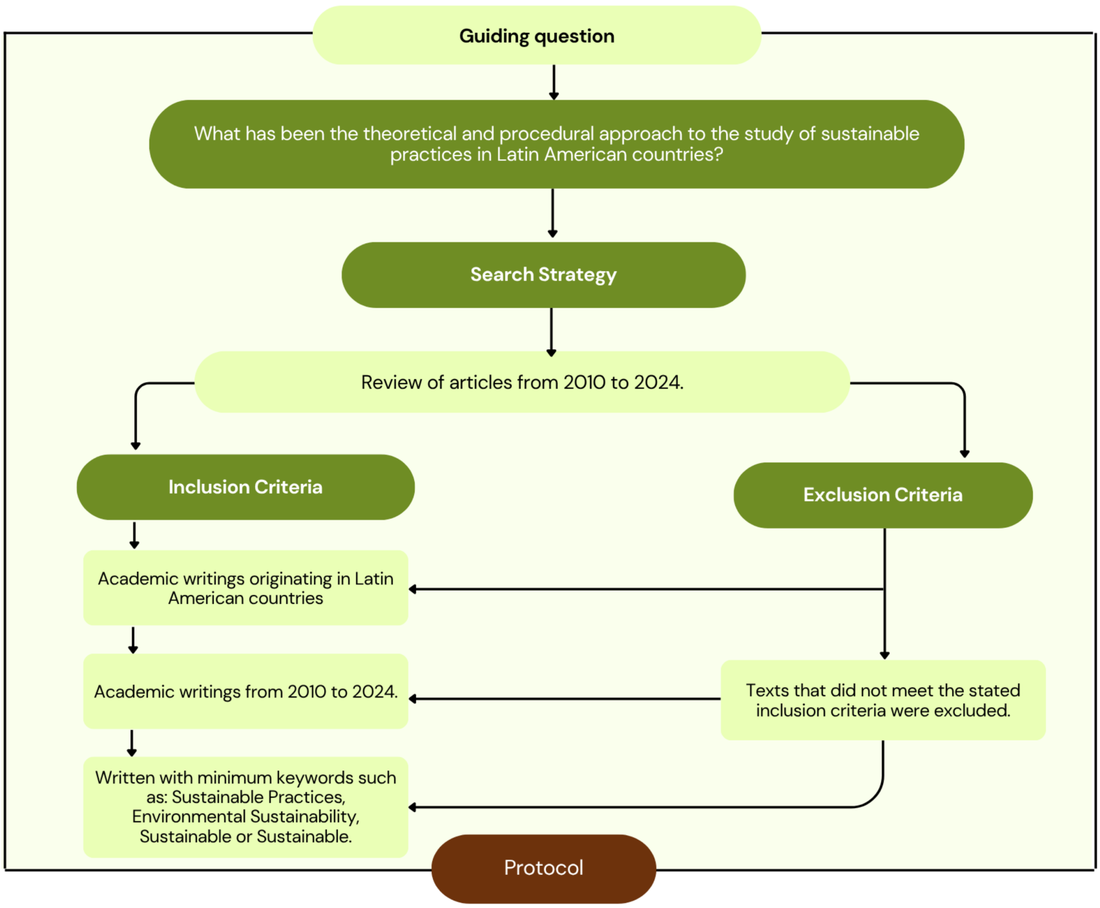


**Figure 1.** Protocol used in this study.

According to the protocol presented in Figure 1, this study seeks to answer the following research question:

> *What has been the theoretical and procedural approach adopted in the study of sustainable practices in Latin American countries?*

This question arises from the need to identify the epistemological currents, conceptual approaches, and paradigms that have shaped studies on Environmental Sustainability (ES) and Sustainable Practices (SP), including the influence of perspectives such as the dialogue of knowledges, agroecology, alternative economic models, and educational processes, among others. Likewise, from a methodological perspective, this research examines aspects related to study type, data collection techniques, and participant populations. Consequently, the question aims to articulate a comprehensive analysis of research on ES and SP in Latin America.

**Table 1.** Analytical Categories of Environmental Sustainability (ES).

| No. | Category | Description |
|---|---|---|
| 1 | Epistemological Constructions on Environmental Sustainability (ES) | This category refers to the diverse ways in which Sustainable Practices (SP) have been understood and addressed, their applications in fields of study, and interpretations based on the methods used. |
| 2 | SP and dialogue of knowledges | It analyzes SP and their relationship with the exchange and integration of traditional community knowledge within the sustainable paradigm. Likewise, it examines their relationship with scientific knowledge to establish holistic approaches. |
| 3 | SP and studies on biological diversity | The relationship between sustainable practices and biodiversity conservation is explored; this includes studies on conservation strategies for the protection and use of natural resources. |
| 4 | SP and formal educational processes | Educational strategies for strengthening environmental sustainability within formal education systems, oriented towards Environmental Education (EE), are addressed. |
| 5 | SP, agroecology for food sovereignty and security | Agroecology is linked as a sustainable strategy in peasant and local production systems. The implementation of new technical strategies is analyzed. |
| 6 | ES within the framework of environmental conflicts | Works addressed within the context of conflict are incorporated, examining the causes and consequences of environmental challenges to influence the search for resolution strategies. |
| 7 | ES and alternative socioeconomic models | Research processes seeking the creation of solid alternatives to generate a balance between sustainability and economics (e.g., rural cities) are integrated. |
| 8 | ES, resistance, and communities | Processes of resilience, empowerment, and struggle of communities organizing to influence participatory spaces regarding environmental challenges are considered. |

Based on the data collected, the information was organized according to several factors such as year of publication, country of origin, type of document and study, population involved in each investigation, and the review or reflection presented in each article. These factors make it possible to identify trends and patterns in academic production related to the topic during the period 2010–2024.

For data analysis, Python was employed as a quantitative tool, enabling rigorous data processing through advanced statistical techniques. Additionally, a set of analytical categories was structured based on the emerging patterns identified within the reviewed corpus. This software facilitated the systematization of results according to a series of analytical categories related to Environmental Sustainability and Sustainable Practices in Latin America (Table 2).

The information obtained was organized into emergent categories that arose during the review process, summarized in Table 1.

## 3 Results and Discussion

The systematic review of 200 articles on Sustainable Practices (SP) and Environmental Sustainability (ES) in Latin America (LATAM) reveals a dynamic and evolving landscape. Between 2010 and 2024, academic production has focused on four main categories: scientific articles, research books, academic conference proceedings, and theses or dissertations.

As shown in Figure 2, scientific articles dominate the output, with notable peaks in 2016 and 2020, indicating a significant increase in research activity during those years. It is worth noting that research books and academic conference proceedings also show considerable variability, particularly in 2016, while undergraduate and graduate theses have grown substantially in recent years, especially in 2021 and 2022, reflecting a stronger emphasis on research at both undergraduate and postgraduate levels.

These findings suggest a growing interest and sustained effort in the study of environmental sustainability across the region, contributing significantly to academic knowledge and the implementation of sustainable practices (Figure 2).

The geographic distribution of bibliographic production in Latin America (LATAM), shown in Figure 3, reveals a clear concentration in Colombia and Mexico, with 97 and 58 publications, respectively. This prominence positions Colombia as the leading country in research on Sustainable Practices (SP), followed closely by Mexico. Argentina, with 12 publications, and Chile and Ecuador, with 6 each, represent a moderate contribution. In contrast, countries such as Bolivia, Brazil, and Venezuela each contributed 5 publications, while Peru, Cuba, and Uruguay show significantly lower output, with 3, 2, and 1 publications, respectively.

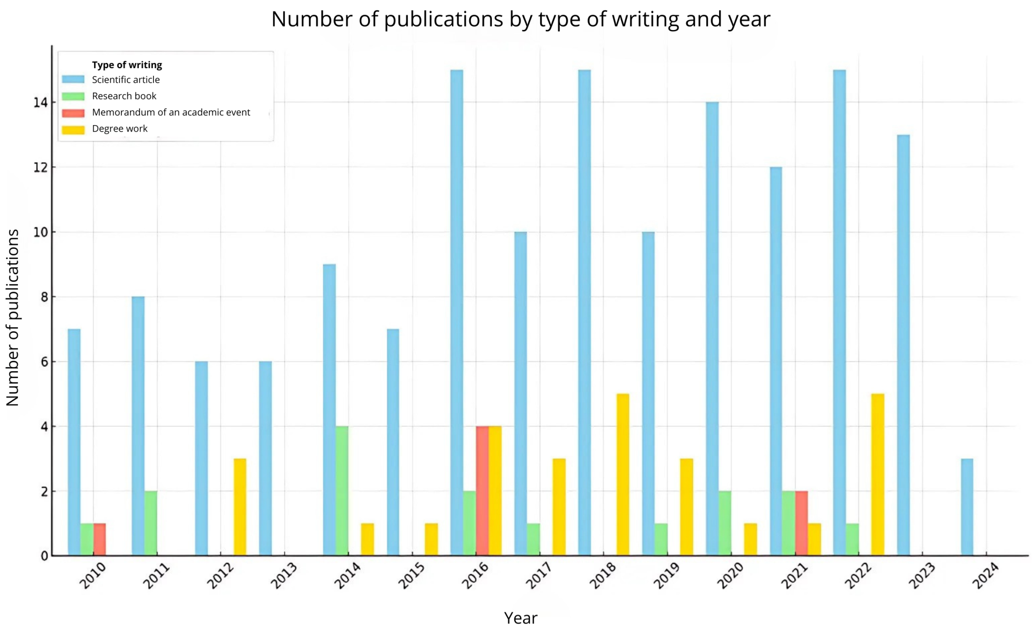


**Figure 2.** Number of publications by type of document and year.

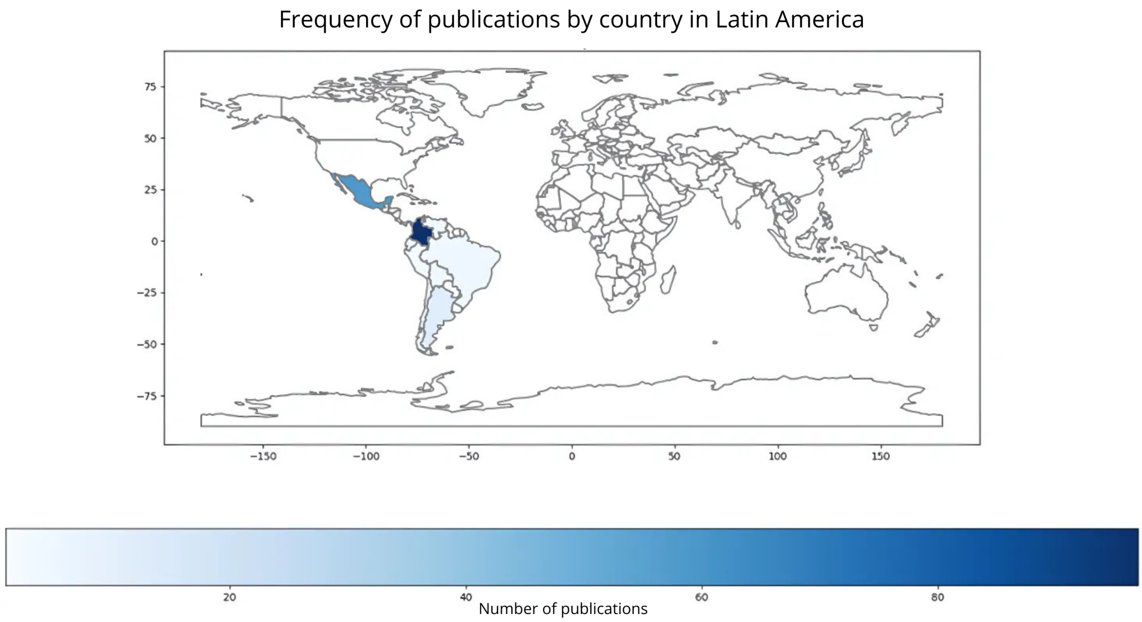


**Figure 3.** Graphical representation of the incidence of publications by country in Latin America.

The distribution of academic publications across Latin America highlights the notable dominance of Colombia and Mexico, which together account for more than half of the total reviewed works, suggesting a strong emphasis on research and the development of sustainable practices in these two countries. Conversely, the lower publication rates in countries such as Peru, Cuba, and Uruguay indicate regions with substantial potential for academic growth, emphasizing the need for local and regional collaborative initiatives to enhance both the recognition and advancement of sustainable practices and the overall research output in this field.

# 4 Study Population and Number of Publications

Figure 4 presents the results regarding the target population and the number of publications from 2010 to 2024. Approximately 40 % (75) of the studies focused on peasant, Indigenous, and community groups, addressing key aspects related to territory, ecosystems, and sustainable practices (Auer et al., 2022). Likewise, works such as that of Calvo (2019) propose the creation of sustainable alternatives and practices in the *Zona de Reserva Campesina del Valle del Río Cimitarra*.

Table 2 identifies the top 10 journals with the highest number of publications on Sustainable Practices (SP). *Gestión & Ambiente* leads with 8 articles, followed by *Cuadernos de Desarrollo Rural* with 6, and *Community Development Journal* with 5, highlighting key topics such as environmental management and rural development. The data reveal that research on SP is well distributed across various fields of study, which is crucial for achieving a holistic understanding and fostering the development of sustainable practices within territories.

On the other hand, organizations and social associations represented 25 % of the studies, indicating the existence of inter-institutional research that acknowledges the role of social actors as active agents in communities, particularly in the development of processes oriented towards community-based economies (Payarés-Comas and Garnica-Morales, 2010).

**Table 2.** Top 10 Latin American journals with the highest number of publications in PS Sustainable Practices.

| No. | Journal | Number of Publications |
|---|---|---|
| 1 | Gestión & Ambiente | 8 |
| 2 | Cuadernos de Desarrollo Rural | 6 |
| 3 | Community Development Journal | 5 |
| 4 | Estudios Sociales: Revista de Alimentación Contemporánea y Desarrollo Regional | 4 |
| 5 | La Granja: Revista de Ciencias de la Vida | 3 |
| 6 | Sociedad y Ambiente | 3 |
| 7 | Repositorio Institucional de la Universidad Nacional de Colombia | 3 |
| 8 | Agricultura, Sociedad y Desarrollo | 2 |
| 9 | Biografía. Escritos sobre la Biología y su Enseñanza | 2 |
| 10 | Bitácora Urbano Territorial | 2 |

Additionally, 8 % of the studies focused on mitigating the negative effects of anthropocentric practices on ecosystems and biological diversity, with notable contributions such as those by Daga et al. (2022) and Bernal (2017). Finally, studies involving public sector entities emphasize their contribution to environmental sustainability through models of territorial planning and social construction, as evidenced in the research by Rincón-Martínez (2012).

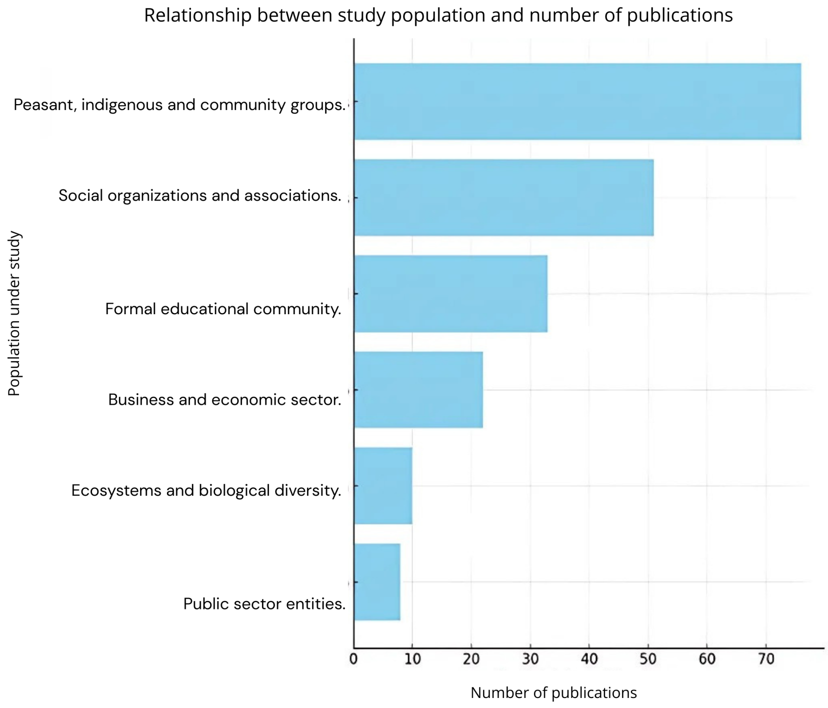


**Figure 4.** Relationship between study population and number of publications.

## 5 Research Methodologies

Figure 5 shows that qualitative studies predominate with more than 160 publications, reflecting a marked preference for methods that enable in-depth, contextualized exploration. Mixed-methods studies rank second, with nearly 30 publications, indicating efforts to combine approaches for a more comprehensive view. By contrast, quantitative studies are the least common, with fewer than 10 publications, suggesting a lower inclination toward measurement-centered and statistical analyses.

To strengthen the field, it would be beneficial to balance study types by promoting methodological diversity and complementarity between qualitative and quantitative approaches.

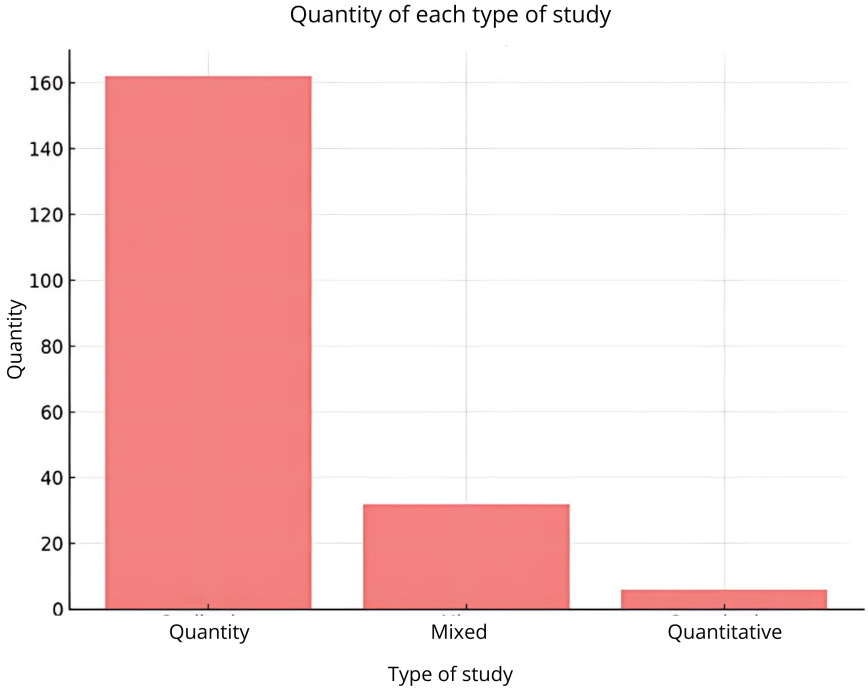


**Figure 5.** Results by study type.

## 6 ES in Latin America and the Caribbean

ES in Latin America and the Caribbean challenges the foundations of modern Western thought, extractivist development, and colonial logics that have shaped relationships between modern society and nature. Emerging currents of thought in the LATAM and Caribbean context face a crucial challenge—and opportunity—in rethinking development models to ensure ES in specific territories. As Slutzky (2012) notes, the crisis is an articulated process that requires adopting a pathway toward ES as a transformative solution.

Within this panorama, it is urgent to reverse absolutist trends that have dominated environmental dynamics in LATAM and the Caribbean (Leff, 2009), where the region's biocultural wealth demands an approach that integrates the dialogue of knowledges, promoting sustainable practices (SP) and alternatives to development grounded in environmental justice and respect for ecosystems (Romero and Vázquez, 2012).

Among the key references in LATAM are environmental rationality, which critiques an extractivist and technocratic model that has subordinated territories and traditional knowledge of Indigenous and local peoples (Leff, 2004), and post-extractivism and environmental ethics, which propose an ES approach rooted in political commitment to ecological and social justice (Gudynas, 2014).

ES, social-justice struggles, and educational processes have been pillars of an alternative civilizational project to the modern hegemonic model, including Paulo Freire's critical and emancipatory education (Paiva, 2004). This serves as a bridge for the dialogue of knowledge, challenging the hegemony of Western scientific knowledge and integrating the worldviews of Indigenous and peasant communities (Cruz, 2020). From this perspective, education becomes a political, ethical, and environmental act capable of rebuilding the bonds between humans and nature.

These postulates bring together ethics, education, social justice, dialogue, and culture around environmental dynamics, opening new ways of dwelling and co-dwelling in harmony with territories and nature across LATAM and the Caribbean—also known as *Abya Yala*. Hence, it is necessary to analyze how ES has been approached through SP in LATAM and the Caribbean via academic research in this context.

Figure 6 displays the distribution of analytical categories in studies on SP, offering a detailed view of predominant areas of focus. Each category represents a crucial facet of ES and shows the number of studies devoted to that topic. This distribution not only reflects research priorities and trends but also highlights areas needing greater attention and development. Below is a detailed analysis of each category, from the most to the least represented, to better understand current dynamics and approaches in the ES field.

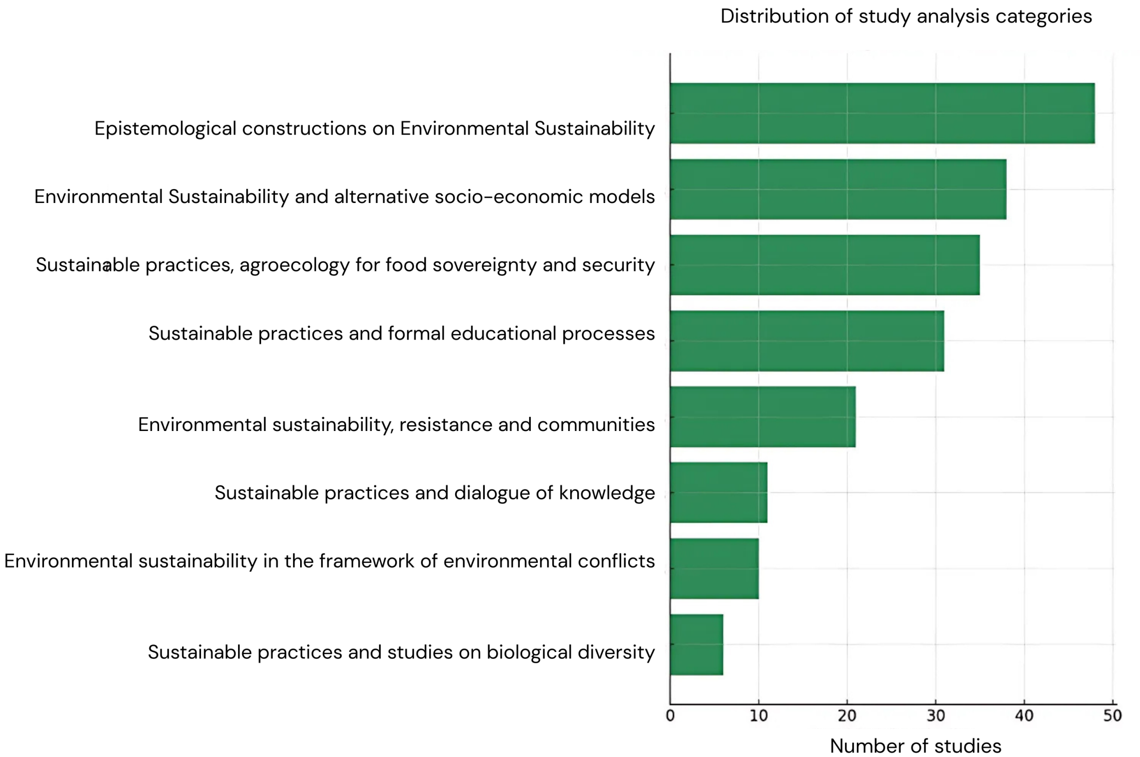


**Figure 6.** Results by analytical category on ES in LATAM. Source: Authors.

## 6.1 Epistemological Constructions on ES

The analysis of epistemological constructions on ES encompasses a variety of studies offering critical approaches and diverse methodologies. A notable example is the work associated with Manfred Max-Neef, which critiques productivism and extractivism in LATAM and advocates for human development grounded in ecological foundations at the local scale, challenging macroeconomic models historically imposed since colonial times (Valenzuela-Van Treek et al., 2021).

A significant model is Environmental Education (EE) for sustainable human development in the Chontal community of Olcuatitán, Tabasco. Rooted in tradition and local knowledge, this model promotes a critical, constructivist EE adapted to the community's ecological and cultural conditions. Its implementation has proven effective in forming community groups and generating sustainable projects, underscoring the importance of contextualized education for lasting impacts.

Another line of inquiry on subjectivation and citizenship in Latin American environmental territories explores integrating politics and epistemology for social and epistemic emancipation. It stresses recognizing diverse actors and forms of knowledge, employing ethnographic methodologies to challenge hegemonic scientific visions, and proposing systematization of experiences that acknowledge and reconstruct practices of historically dominated sectors.

In business, studies on replicating sustainability best practices in fast-moving consumer goods companies in Colombia, and environmental sustainability strategies in human resources, reveal how organizations can align their practices with Sustainable Development Goals—albeit often from a Eurocentric perspective (Gómez, 2014).

Collectively, these studies foster an understanding of socio-ecological resilience and the need to develop more robust, less vulnerable systems to confront contemporary environmental uncertainty. They also demonstrate the richness and diversity of ES approaches, highlighting the importance of integrating local, participatory, and critical knowledge to address environmental challenges holistically and effectively.

## 6.2 ES and Alternative Socioeconomic Models

The relationship between ES and alternative socioeconomic models is fundamental for addressing current global and local challenges. One example is Max-Neef's framework of fundamental human needs, together with Amartya Sen's human development theory, both emphasizing the importance of economic, cultural, and social dimensions in development. These theories suggest designing economic policies that account for social and cultural conditions to more effectively and sustainably address poverty (Valenzuela-Van Treek et al., 2021).

Community-based tourism with an environmental focus illustrates how alternative models can integrate sustainability, conserve nature, and strengthen local communities through education and participation—experiences in Colombia show that such tourism can generate sustainable economic benefits while preserving natural environments.

Water-resource management in specific industries—e.g., tanneries in Villapinzón—demonstrates how SP can improve economic efficiency and reduce environmental impact. Aligning environmental management policies with business strategies shows that corporate sustainability is not only viable but necessary for long-term survival.

In urban areas, environmental sustainability indices help identify and address priority interventions. Analysis of urban sustainability in the Mexico City megalopolis shows how public policies can improve distribution and management in the face of current sustainability challenges, tackling environmental and socioeconomic issues while considering climate-change mitigation and ecological-footprint reduction.

In rural contexts, socio-spatial practices and preservation through sustainability are vital. Agroecotourism in Mexico and sustainable-development strategies in Bolivia's southern highlands—such as quinoa production—illustrate how sustainable agriculture, together with ecological and cultural activities, can promote ES and enhance rural quality of life.

In Colombia, initiatives like *Mercados Verdes* integrate education, management, and ES, fostering more equitable economic development by promoting eco-products and responsible commerce—an opportunity for small and medium enterprises to adapt to new consumption demands (Diaz et al., 2016). A study in El Cocuy, Boyacá highlighted the participation of social groups in the production and consumption of foods grown using traditional practices, encouraging responsible land use and reinforcing a harmonious relationship among nature, society, and culture (Castillo et al., 2023).

These alternative models in LATAM and the Caribbean not only address emerging needs but also promote a fairer, more sustainable economy, underscoring the importance of local development and cultural preservation as pillars for achieving ES.

## 6.3 Sustainable Practices, Agroecology, and Food Sovereignty / Security

SP within agroecology represents a holistic approach spanning social, economic, and cultural dimensions. Deeply rooted in ancestral knowledge and complemented by contemporary innovations, these practices aim to ensure the food sovereignty and security of rural, peasant, and indigenous communities. Studies show that implementing such practices can yield positive outcomes in agricultural productivity, environmental conservation, and social strengthening (Cardona and Sierra, 2023; Chaga, 2012; Chaparro, 2017).

In southeastern Buenos Aires (Argentina), research on farmers' understanding of ecosystem services and SP adoption found that higher educational level and off-farm residence increased the likelihood of adoption, whereas economic uncertainty and operational complexity posed barriers—underscoring the need for technical/financial support and spaces for shared learning (Auer et al., 2022).

In Colombia's *Zona de Reserva Campesina del Valle del Río Cimitarra*, community organization and resistance have advanced food sovereignty and improved living conditions, emphasizing public policies that revalue family economies and facilitate the transition to agroecology (Calvo, 2019).

In Boyacá (Colombia), research on food autonomy in family farms documented a shift toward agroecology, strengthening agrobiodiversity, seed conservation, and community self-governance—highlighting interconnections among agroecology, ancestral knowledge, and autonomy (Lucco, 2019).

In Mexico and Colombia, indigenous medicine and cultural practices linked to agroecology proved essential for community health and indigenous health sovereignty, notably during crises such as the SARS-CoV-2 pandemic (Muñoz, 2022).

Economically, green markets and short food supply chains contribute to the sustainability of food systems. The *Mercado Verde* project in Morelos (Mexico) promotes sustainability, responsible consumption, and fair trade, strengthening local economies and sustainable production.

In Ecuador, ES and SP in horticultural systems in San Joaquín were significantly strengthened by ancestral practices such as crop rotation, associativity, and biodiversity, improving production and the quality of life of peasant families (Pacheco and Ortiz, 2022).

Transitioning to agroecology entails transforming the social and economic structures that underpin agricultural production. Movements for food sovereignty and agroecology show that more just, sustainable food systems are possible through community organization, transnational solidarity, and the promotion of a shared peasant identity (Camacho et al., 2022).

## 6.4 SP and Formal Educational Processes

Integrating SP into formal education is an innovative and necessary approach to forming environmentally aware and responsible citizens. Research highlights how educational strategies supported by ICTs are transforming traditional teaching by fostering direct connections between students and their surroundings (Ruiz, 2021).

Formal education provides fertile ground for creating and applying SP that encourage student participation in community projects; contextualized environmental/sustainability programs; and environmental management systems in universities—proven effective in shaping citizens committed to sustainable development (Tuay Sigua et al., 2016; Marín, 2011).

A notable case is the University of Chile, where institutional collaboration and local community participation have promoted social responsibility and sustainable consumption (Severino-González et al., 2021). School-based horticultural systems and eco-art also integrate sustainability with learning and artistic expression (Carnicer et al., 2020; Bernaschina, 2023).

Flórez (2012) sought to integrate social actors in the municipalities of Sugamuxi and Tundama to understand and develop the environmental dimension locally, underscoring collaboration between schools and communities to achieve shared goals in EE and sustainability.

At the university level, the National University of Colombia has worked to structure sustainability within its Faculty of Engineering. Grounded in critical realism and Anthony Giddens' structuration theory, this initiative aims to train professionals capable of meeting sustainable-development challenges and proposing innovative solutions (Cortés, 2018).

## 6.5 ES, Resistance, and Communities

Many human groups have shown remarkable resilience in the face of ecological, social, political, and economic challenges. For example, Barreiro Zamorano et al. (2021) examine biocultural heritage as a sustainable alternative in Mexico's Malintzin National Park, illustrating how ES is woven together with communities to adapt and resist environmental change. Across LATAM and the Caribbean, women's organizations have successfully confronted contemporary challenges through *Buen Vivir* (Cerna et al., 2022).

Community resilience has fueled movements that empower new generations by blending ancestral knowledge with contemporary science. In Brazil, Fauth and Antunes (2016) highlight the value of traditional knowledge as the basis for inclusive, resilient sustainability strategies. In Boyacá (Colombia), Lucco (2019) documents peasant communities' struggles for food security and sovereignty amid regional inequality and hunger.

In Tierradentro (Colombia), the Yaquivá Reserve has applied traditional knowledge to design sustainable strategies, integrating nature, culture, and education into a community Life Plan (Franco, 2021), strengthening identity and autonomy and underscoring the importance of social inclusion and community participation within a framework of customary law (Martínez, 2022).

Participatory mapping has been pivotal in indigenous and Afro-descendant communities' struggles for territorial and resource rights in LATAM, facilitating spatial representation and resource governance. It has been discussed in international fora as a form of resistance and recovery of cultural practices with an ES focus (Hale and Barry, 2013).

Women's leadership is vital in these processes. Cerna et al. (2022) on *Buen Vivir* in Paraguay emphasize women as agents of change in climate-change mitigation, promoting SP from a Guaraní worldview. Experiences in Sumapaz (Bogotá) describe the importance of the dialogue of knowledge in ES processes, through effective collaboration between institutions and local communities that strengthens traditional knowledge and builds trust and cooperation—key to robust community resistance to environmental challenges (Bayona and Pachón, 2014).

These studies underscore communities' central role in advancing ES, integrating traditional and contemporary approaches to develop resilient, adaptive strategies for today's challenges.

## 6.6 SP and the Dialogue of Knowledge

The dialogue of knowledge articulates cognitive and cultural diversity with the study's analytical categories, highlighting communities as bearers of knowledge that promotes harmonious relations with nature and other forms of life. This rootedness and resistance manifest in territorial defense, contributing to what some researchers describe as a "radical reconstruction of being, power, and knowledge" (Semanate and Alfonso, 2024).

Further studies (Sánchez-Zárate, 2016; Vergara, 2020) show how ethno-education fosters sustainable development in Indigenous and rural communities through ethnotourism and the sociocultural management of agroecosystems. The latter focuses on sociocultural management grounded in traditional knowledge and its effects on soils in agroecosystems in Guacarí (Valle del Cauca, Colombia), offering alternatives to problems such as soil degradation through peasant knowledge, agroecosystem characterization, and related processes.

## 6.7 ES within the Framework of Environmental Conflicts

This analysis reveals significant information on the challenges communities face regarding the environmental dimension and their role in articulating ES. Key concepts include natural-resource management, mitigation of negative impacts such as extractivism (Lehnert and Carrasco, 2020), and the preservation of biodiversity and quality of life in peasant, Indigenous, and local communities.

Rodríguez-Enciso (2020) examines environmental conflict from political ecology, focusing on reconciling conservation goals in peasant territories within Tinigua National Natural Park. The study proposes incorporating community-based forest management experiences, recognizing tenure rights, and implementing forest governance systems—crucial for aligning conservation with community well-being.

Additional conflicts identified stem from excessive exploitation of natural resources, irregular issuance of environmental licenses, poverty, dispossession, and forced displacement—factors that destabilize environmental dynamics, particularly in hydro-extractivist contexts (Luna-Nemecio, 2023).

A noteworthy example is Bocarejo (2022) on the Magdalena River, which sought to consolidate a participatory framework integrating SP as an effective response to environmental conflicts, promoting balance between conservation and community development. This work intertwines analyses of causes and consequences of changes in water quality with sustainable alternatives aimed at conflict resolution around this environmentally significant river.

## 6.8 SP and Studies on Biological Diversity

In the realm of SP and biological diversity, several studies seek to harmonize human activities with nature conservation. One relevant example is the development of conservation strategies to protect paramo ecosystems in the upper Bogotá River basin (Colombia), which have faced significant socio-environmental conflicts (Bernal, 2017).

Biodiversity—essential to ecosystem health and human well-being—intersects with ethnobotany, a body of traditional knowledge linking the dialogue of knowledge with biological and cultural conservation (Farfán and Valderrama, 2023; Pachón-Barbosa et al., 2021).

The relationship between SP and biodiversity appears in activities such as agroecology and the dialogue of knowledge. An example is the adaptation of guidelines for conserving oak (*Quercus humboldtii*) in the Guantivá–La Rusia–Iguaque conservation corridor, integrating local practices and views with legal, political, and institutional criteria (Avella et al., 2013).

Other studies intersect multiple categories affecting biodiversity conservation, ES, and community economies—for instance, assessing the availability of adventitious roots of three wild species harvested for handicrafts in Santa Elena (Antioquia, Colombia) (Benavides and Hernández, 2015), providing a biodiversity-studies framework to understand demand for these roots and their sustainable use as raw material for utilitarian objects with economic value.

These community-centered studies and the creation of SP are key to advancing effective ES implementation, tailored to specific contexts and contemporary challenges.

### 6.9 Potential Biases and Limitations of the Study

In this systematic review, acknowledging limitations and biases enables us to question and reaffirm the standpoint and purpose from which these analyses are constructed, thereby avoiding reductionist, fragmented, or detached views of the realities surrounding Environmental Sustainability (ES) and Sustainable Practices (SP) in Latin America. Although grounded in a rigorous systematic review, the present study is not exempt from limitations that may affect the interpretation of its findings. Below are several biases and methodological constraints that could influence the scope of the results:

**Restricted source coverage.** The selection of articles was conducted through open-access databases—Google Scholar, Redalyc, SciELO, Dialnet, among others—using keywords such as *environmental sustainability* and *sustainable practices* in Latin America. However, reliance on specific databases entails access bias in relation to the broader scientific output. This approach excludes studies indexed in higher-impact international databases such as Scopus or Web of Science, limiting engagement with globally referenced research. Moreover, privileging open-access sources may bias the corpus against influential studies published in paywalled journals. Consequently, access to research subjected to more rigorous peer review may be constrained, potentially affecting the representativeness of the analysis.

## 7 Conclusions

The qualitative analysis underscores that Sustainable Practices (SP) in Latin America (LATAM) have advanced significantly, adapting to the region's cultural, social, and biophysical particularities. This evolutionary process has enabled these practices to consolidate as mechanisms for achieving community development that upholds social equity and maintains a harmonious relationship with the natural environment. The results show how diverse communities—from peasant to Indigenous—have adopted SP, integrating approaches that promote biodiversity conservation as well as the safeguarding of traditional cultures and ways of life.

The dialogue of knowledge emerges as an essential element in articulating ES, enabling interaction between ancestral and scientific knowledge. This convergence has proven effective for resource management and biodiversity conservation, particularly in areas where local communities play a leading role. It reinforces cultural identity, equips communities to confront and adapt to contemporary environmental challenges, and strengthens resilience. In this sense, it complements ongoing research in LATAM by creating participatory spaces—across peasant, Indigenous, and urban communities—that actively contribute to building ES strategies in community, policy, educational, economic, and social domains.

Research in this field focuses primarily on peasant, Indigenous, and local communities, emphasizing their pivotal role in implementing and sustaining SP—approximately 40 % of the articles reviewed. This central finding highlights the capacity for resistance among local, peasant, and Indigenous communities in the face of ecological, social, and economic challenges. It also illuminates how ES is not reducible to mere resource management or technological application but converges with political dimensions of autonomy and re-existence developed by Latin American communities.

Community resistance is evident both in the preservation of traditional practices and in the ability to adapt and thrive in adverse contexts. A clear example is the ongoing struggle for territorial rights and the pursuit of alternatives to meet basic needs—such as agroecology for food sovereignty and security. Supporting these communities in conserving SP is crucial, recognizing their role in promoting fair and equitable development alternatives.

The incorporation of SP into formal education emerges as a vital strategy for forming environmentally aware and committed citizens. Through the integration of information and communication technologies (ICTs) and participation in community projects, educational institutions are transforming how students engage with their surroundings, preparing new generations to address environmental challenges from a local, practical, and transformative perspective.

The importance of developing public policies is emphasized—policies that not only facilitate the implementation of SP but also respect and value the region's cultural and ecological diversity. Such an integrated approach is key to advancing toward a sustainable development pathway that benefits both local communities and the environment as a whole.

From a quantitative standpoint, the analysis identifies significant patterns and trends in academic and scientific output on SP and ES in LATAM during 2010–2024. Notable increases in publications occurred in 2016, 2020, 2021, and 2022, suggesting growing interest aligned with emerging trends in ES and SP. Countries such as Colombia and Mexico concentrate the largest number of studies, indicating vibrant research agendas and expanding lines of inquiry aligned with national realities and alternatives. In contrast, Peru, Cuba, and Uruguay display lower output, underscoring the need to foster research in these contexts to strengthen regional focus and reduce gaps in access to and production of knowledge.

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## Author Contributions

**M.C.C.R.:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing–original draft, Writing–review & editing. **L.P.A.C:** Conceptualization, Formal analysis, Investigation, Methodology, Writing–original draft, Writing–review & editing. **D.A.V.:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing–original draft, Writing–review & editing. **N.A.P.B.:** Conceptualization, Investigation, Project administration, Supervision, Validation, Visualization, Writing–original draft, Writing–review & editing.

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Quality of life and sustainability



# The role of NEAZDP on social mobility of poverty in Yobe State of Nigeria

# El papel del NEAZDP en la movilidad social de la pobreza en el estado de Yobe, Nigeria

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**Abstract**

Yobe State in Nigeria, marked by socio-economic challenges such as climate variability and poor infrastructure, provides a compelling context for assessing poverty reduction strategies. This study evaluates the effectiveness of the Northeast Arid Zone Development Program (NEAZDP) as a poverty alleviation strategy using 2023 cross-sectional household survey data from 322 households selected through a multi-stage sampling technique. Data collection was carried out using a well-structured questionnaire coupled with interview schedules. The analysis employed both the Foster-Greer-Thorbecke (FGT) poverty index and the Alkire-Foster multidimensional poverty index (MPI) to measure poverty. Results reveal that NEAZDP has had a significant impact on reducing both unidimensional and multidimensional poverty among participants. The proportion of beneficiaries below the poverty line decreased substantially during the program, although a slight increase was noted toward the program's conclusion. Furthermore, multidimensional poverty levels among NEAZDP beneficiaries were significantly lower compared to those in spill-over and control groups, indicating improvements in access to education, healthcare, and income-generating opportunities. Despite these successes, the study identified persistent challenges in areas such as standard of living, empowerment, and environmental sustainability. In conclusion, NEAZDP has made notable progress in enhancing socio-economic conditions and social mobility in Yobe State. However, for its impact to be sustained, there is a need for continuous, targeted interventions and better policy integration. Strengthening these areas can help ensure the long-term success of poverty alleviation efforts and promote inclusive development across the region.

***Keywords***: Development, Intervention, Poverty Alleviation, Sustainability, Nigeria.

**Resumen**

El estado de Yobe, en Nigeria, caracterizado por diferentes desafíos socioeconómicos como la variabilidad climática y la infraestructura deficiente, ofrece un contexto relevante para evaluar las estrategias de reducción de la pobreza. Este estudio analiza la efectividad del Programa de Desarrollo de la Zona Árida del Noreste (NEAZDP) como estrategia de mitigación de la pobreza, utilizando datos de una encuesta transversal realizada en 2023 a 322 hogares, seleccionados mediante una técnica de muestreo en varias etapas. La recolección de datos se efectuó mediante cuestionarios estructurados y entrevistas programadas. El análisis empleó tanto el índice de pobreza Foster-Greer-Thorbecke (FGT) como el índice de pobreza multidimensional Alkire-Foster (MPI) para medir la pobreza. Los resultados revelan que el NEAZDP tuvo un impacto significativo en la reducción de la pobreza tanto unidimensional como multidimensional entre los participantes. La proporción de beneficiarios por debajo de la línea de pobreza disminuyó sustancialmente durante la ejecución del programa, aunque se observó un ligero incremento hacia su finalización. Además, los niveles de pobreza multidimensional entre los beneficiarios del NEAZDP fueron significativamente menores en comparación con los grupos de desbordamiento y de control, evidenciando mejoras en el acceso a la educación, la atención médica y las oportunidades de generación de ingresos. A pesar de estos avances, el estudio identificó desafíos en aspectos como el nivel de vida, el empoderamiento y la sostenibilidad ambiental. En conclusión, el NEAZDP ha logrado avances importantes en la mejora de las condiciones socioeconómicas y en la promoción de la movilidad social en el estado de Yobe. Sin embargo, para mantener su impacto, hay que implementar intervenciones continuas y específicas, así como una mejor integración de las políticas públicas. El fortalecimiento de estos aspectos puede garantizar el éxito a largo plazo de los esfuerzos de mitigación de la pobreza y fomentar un desarrollo inclusivo en toda la región.

***Palabras clave***: Desarrollo, intervención, alivio de la pobreza, sostenibilidad, Nigeria.

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# 1 Introduction

Yobe State, located in northeastern Nigeria, remains entrenched in poverty exacerbated by its arid and semi-arid climate, limited infrastructure, and long-standing socio-economic challenges (Gadzama, 2017; Umar, 2024; Madaki et al., 2024). In response, the Northeast Arid Zone Development Program (NEAZDP) was implemented to promote economic empowerment and sustainable development among vulnerable rural populations (Mukhtar et al., 2017; Galadima and Isa, 2020). While the program has made notable investments in agriculture, entrepreneurship, and rural infrastructure, its effectiveness in driving social mobility and sustainable poverty reduction remains underexplored.

Despite NEAZDP's interventions, key questions persist about the extent to which it has improved livelihoods, income levels, and access to essential services, and whether it has succeeded in fostering long-term economic resilience in the face of persistent climate and security challenges. The unique socio-economic and environmental context of Yobe State—characterized by desertification, food insecurity, and conflict—poses distinct implementation challenges that may limit program impact compared to other regions.

A global comparative lens further enriches discourse. For instance, Brazil's Bolsa Família and India's Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) have demonstrated how integrated social protection and livelihood programs can uplift households from chronic poverty through conditional cash transfers, job creation, and access to services. In Ghana, the Livelihood Empowerment Against Poverty (LEAP) program also mirrors NEAZDP's focus on vulnerable groups but integrates more targeted health and education incentives (Schotte, 2023; Woode, 2024). These international programs highlight the importance of monitoring, adaptability, and policy integration, which are crucial for replicating success in Nigeria's fragile contexts.

Moreover, studies in sub-Saharan Africa suggest that the effectiveness of poverty alleviation programs is context-dependent, with success hinging on community participation, environmental adaptability, and inclusive governance (Ncube et al., 2024; Wudil et al., 2022). As such, Yobe State presents a unique case for evaluating the impact of rural development programs in conflict-prone, ecologically fragile environments.

Therefore, this study seeks to bridge empirical gaps by assessing the role of NEAZDP in enhancing social mobility and reducing poverty—both unidimensional and multidimensional—among its beneficiaries in Yobe State. Specifically, it evaluates the program's impact compared to non-beneficiary groups (spillover and control) using quantitative metrics and qualitative insights. Findings from this research aim to inform evidence-based policymaking, enhance program effectiveness, and contribute to broader strategies for sustainable development and inclusive growth in Nigeria and across sub-Saharan Africa (Orunbon and Adeleke, 2024; Kabari and Nwogo, 2021; Ogbari et al., 2024; Kolawole and Samuel, 2024). Succinctly, the specific objectives are to assess the role of NEAZDP on unidimensional poverty among the beneficiary group and multidimensional poverty status of the beneficiary group against the non-beneficiary group.

# 2 Theoretical Framework

The foundation of this study is grounded in established poverty and development theories that explain the mechanisms through which development interventions like the Northeast Arid Zone Development Program (NEAZDP) influence poverty reduction and social mobility in fragile contexts like Yobe State, Nigeria.

## 2.1 Capability Approach (Amartya Sen)

Sen's Capability Approach redefines poverty beyond income deficiency, framing it as a deprivation of basic capabilities such as education, health, and living standards (Sen, 1999). This theoretical lens is crucial in understanding how NEAZDP interventions in agriculture, education, and infrastructure affect not just income but broader well-being. The approach has been effectively used in rural development studies in sub-Saharan Africa (Mak et al., 2023).

### 2.2 Social Mobility Theory

Rooted in the work of Blau and Duncan (1967), this theory explains how individuals or households change their socio-economic position over time. NEAZDP's emphasis on skill acquisition, entrepreneurship support, and infrastructural access can influence vertical mobility among previously marginalized rural dwellers (Lembi and Yahaya, 2023).

### 2.3 Growth and Redistribution Theory

As highlighted by Bourguignon (2004), growth alone is insufficient to combat poverty unless accompanied by equitable redistribution. This theory aligns with studies indicating that NEAZDP's redistributive components, such as subsidized agricultural inputs and financial empowerment schemes, play a central role in reducing rural inequality (Sadiq et al., 2024).

### 2.4 Multidimensional Poverty Framework (Alkire & Foster, 2011)

This model emphasizes simultaneous deprivations across various domains—education, health, and standard of living—and supports the use of the Multidimensional Poverty Index (MPI) in evaluating the NEAZDP. Empirical applications of this approach in Nigeria have revealed disparities that income-based metrics overlook (Naibbi, 2023; Jellason, 2018).

### 2.5 Demographic Transition Theory

According to Notestein (1945), shifts in population structure influence development outcomes. Large household sizes, rural-urban migration, and dependency burdens in Yobe State may dilute the impact of NEAZDP unless interventions are designed with demographic realities in mind (Cinjel and Kefas, 2024).

## 3 Conceptual Framework

The conceptual framework illustrates the logical relationships between NEAZDP interventions and the study's dependent variables: unidimensional and multidimensional poverty, and social mobility. It is structured around three main pathways:

**Input: NEAZDP Interventions**

- Agricultural support (tools, seeds, irrigation)
- Infrastructure development (boreholes, roads)
- Vocational training and skills acquisition
- Micro-credit and entrepreneurship support

**Mediating Variables**

- Household Demographics (size, dependency ratio, education level)
- Access to Services (schools, healthcare, markets)
- Environmental Conditions (aridity, displacement, insecurity)

These factors influence the rate and depth of poverty reduction.

**Outcome Variables**

- Unidimensional Poverty (measured by income thresholds using FGT index)
- Multidimensional Poverty (MPI domains: education, health, standard of living)
- Social Mobility (changes in income class, occupational shift, education level over time)

This framework allows a structured analysis of how development programs produce variable poverty outcomes depending on demographic and structural factors. It also guides the use of both FGT and Alkire-Foster methodologies for analyzing poverty levels and program impact.

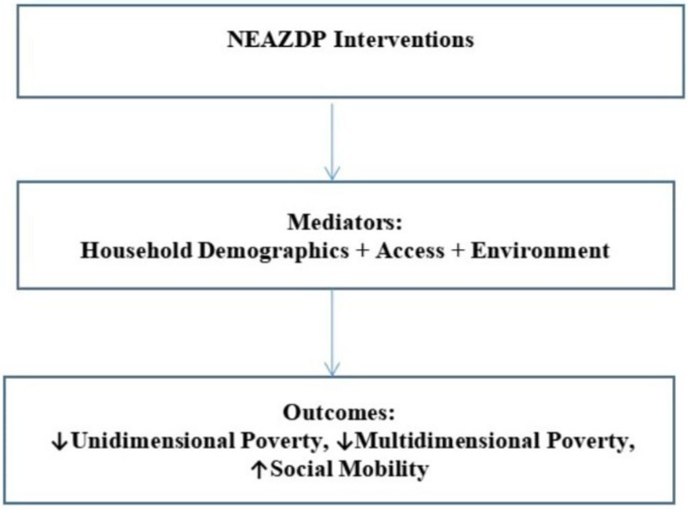



**Figure 1.** Conceptual framework.

# 4 Empirical Review

This section synthesizes empirical evidence on the effectiveness of the Northeast Arid Zone Development Program (NEAZDP) in promoting poverty alleviation and social mobility among beneficiaries in Yobe State, Nigeria, using current and context-relevant studies from 2019 to 2024.

## 4.1 Poverty Reduction and Livelihood Enhancement

Studies indicate that NEAZDP has been instrumental in providing sustainable livelihoods for rural communities in Yobe State by promoting agricultural support, water supply, and environmental conservation (Mukhtar et al., 2017). The program's success in mitigating soil degradation and desertification has contributed to improved food security, which directly impacts poverty reduction (Danjuma and Daura, 2014). A study by Mukhtar et al. (2017) found that while NEAZDP interventions have improved access to essential services in northern Yobe, sustainable poverty reduction remains a challenge. The authors argue that limited government funding and policy inconsistencies hinder long-term impact.

## 4.2 Social Mobility through Economic Empowerment

Lembi and Yahaya (2023) examined the link between NEAZDP's rural development efforts and upward social mobility. Their study found improvements in occupational standing and educational attainment among participants, especially women and youth, because of interventions in agriculture and entrepreneurship. Yet, they reported limited spillover effects on non-beneficiaries in the same communities.

## 4.3 Multidimensional Poverty Dynamics

According to Naibbi (2023), spatial disparities in access to services such as clean water and education continued to affect multidimensional poverty. His spatial mapping analysis across Yobe State revealed that although NEAZDP beneficiaries had better MPI (Multidimensional Poverty Index) scores than control groups, infrastructural inequality and population pressure diluted these gains in more remote LGAs.

## 4.4 Environmental and Institutional Challenges

Jellason (2018) critically examined environmental challenges such as desert encroachment, land degradation, and food insecurity—factors that undermine long-term NEAZDP success. The study suggested integrating sustainable environmental management into program design, especially for agricultural resilience.

### 4.5 Gendered and Community-Specific Outcomes

Studies by Cinjel and Kefas (2024) explored how cultural and gender norms shape NEAZDP outcomes in different communities. Their research in Mangu and Potiskum LGAs found that men dominated access to capital inputs while women benefited more from vocational training components, pointing to the program's uneven impact.

### 4.6 Policy Implementation and Governance Gaps

Wrona et al. (2023) emphasizes weak institutional capacity and lack of data harmonization as major bottlenecks affecting NEAZDP's efficiency. The study underscores the importance of coordinated monitoring and community engagement for long-term program effectiveness in the region.

## 5 Research Methodology

Yobe State, located in northeastern Nigeria, spans about 45,502 km$^2$ and shares borders with Niger Republic and several Nigerian states (Figure 2). It lies within the Sudano-Sahelian zone, featuring flat terrain and high temperatures, with frequent droughts and desertification risks (Naibbi, 2023; Jellason, 2018). Agro-ecologically, Yobe is a semi-arid region with a short rainy season and poor soil fertility. Farming, primarily rain-fed, focuses on crops like millet and cowpea, alongside livestock rearing. However, low agricultural productivity persists due to environmental constraints (Gadzama, 2017). Economically, the state is largely agrarian, with over 70 % of residents engaged in subsistence farming. Challenges such as insecurity, poor infrastructure, and limited market access have intensified poverty. The region experiences high unidimensional and multidimensional poverty rates (Mak et al., 2023).

The Northeast Arid Zone Development Program (NEAZDP) is operational in the northern part of the state, targeting nine (9) Local Government Areas (LGAs): Bade, Jakusko, Bursari, Geidam, Yunusari, Yusufari, Nguru, Karasuwa, and Machina. For this study, a multi-stage sampling technique was employed to select respondents across three strata: treated (project participants), spill-over (non-beneficiaries in proximate communities), and control groups (distant non-beneficiaries).

In the first stage, four LGAs were randomly selected from the treated group: Bade, Jakusko, Bursari, and Geidam. In the second stage, four LGAs each were purposively selected for the spill-over and control groups, respectively:

**Spill-over LGAs:** Tarmuwa, Nangere, Fune, and Fika, all located within a 20–50 km radius of the intervention sites.

**Control LGAs:** Damaturu, Potiskum, Gujba, and Gulani, situated at distances $\geq$100 km from the intervention areas, following the approach adopted by Sadiq et al. (2020).

From each selected treated LGA, one Development Area (DA) was identified. Subsequently, three clusters were randomly drawn from each DA, resulting in a total of twelve clusters. Within these clusters, two villages were randomly selected, leading to a total of 40 villages across all strata (treated, spill-over, and control).

Using a sampling frame obtained from NEAZDP and validated through a reconnaissance survey (see Table 1), five beneficiaries were randomly selected from each of the 24 treated villages (3 clusters $\times$ 4 LGAs $\times$ 2 villages), yielding a total of 120 respondents for the treated group.

For the non-beneficiary groups (spill-over and control), where no finite sampling frame existed, sample sizes were determined using the Bartlett et al. (2002) formula for sample size calculation (Equation 1). Accordingly, 138 respondents were randomly selected for each of the spill-over and control groups.

In total, the study included 396 respondents, distributed as follows: 120 in the treated group, 138 in the spill-over group, and 138 in the control group.

These groups form the basis for comparative analysis of NEAZDP's impact on poverty and social mobility (Table 1).

Furthermore, a cross-sectional dataset was collected in 2023 using the easy-route cost approach. Data collection was conducted by trained enumerators through a well-structured questionnaire, which was further complemented by an interview schedule to enhance data depth and reliability. Moreover, the objective related to the economic/income (unidimensional) aspect of poverty was achieved using a Foster-Greer-Thorbecke (FGT) index (Equation 2–15) while the objective related to social (multidimension) aspect of poverty was achieved using Alkire and Foster multidimensional poverty index (MPI).

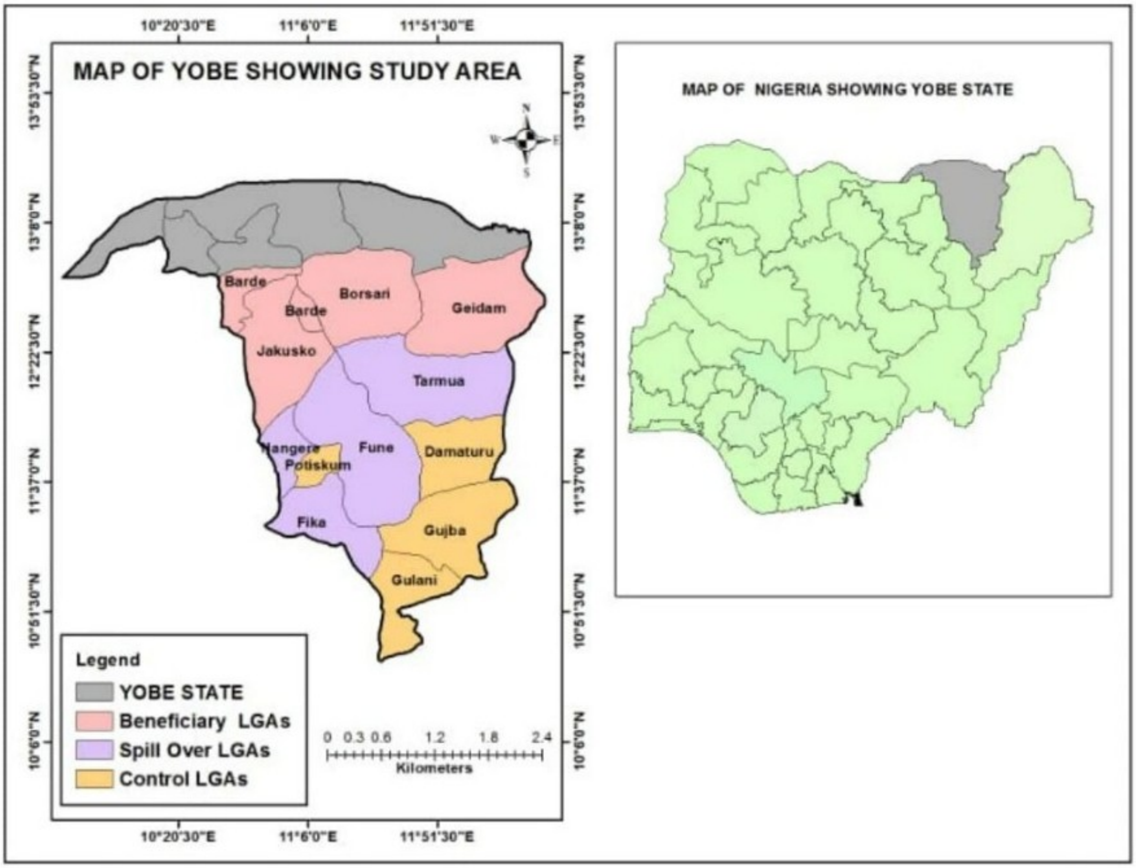



**Figure 2.** Map of the study area.

According to Bartlett's formula, the sample size of the unknown can be generated using the following formula:

$$N_{nb} = \frac{Z^2 * P(1-P)}{e^2} \tag{1}$$

Where, $N_{nb}$ is the sample size of the non-beneficiaries, $Z$ is the Z-statistic at 5 % probability level (1.96), $P$ is the sample proportion (10 %), and $e$ is the error gap at 5 %.

**Table 1.** Sampling frame of both the beneficiaries and non-beneficiaries.

| Category | LGAs | DAs | Cluster villages | Villages | SF | SS |
|---|---|---|---|---|---|---|
| Beneficiary (Treatment) | Bade | Dagona | Dala | Gabarwa | 15 | 5 |
| | | | | Mainiya | 15 | 5 |
| | | Tagali | Lafiyami | Madamuwa | 15 | 5 |
| | | Bizi | Murza | Misilli | 15 | 5 |
| | Bursari | Dumburi | Dadigar | Baya Mallum | 15 | 5 |
| | | | | Diga | 15 | 5 |
| | | Gadine | Gamsa West | Gamsa East | 15 | 5 |
| | | Daskum | Gangawa | Kagadama | 15 | 5 |
| | Geidam | Balle | Bayamari | Malango | 15 | 5 |
| | | | | Kelluri | 15 | 5 |
| | | Damaya | Mobarti | Gallaba | 15 | 5 |
| | | Ajiri Dapchi | Ajiri Geidam | Matakuskum | 15 | 5 |
| | Jakusko | Muguram | Jaba | Dagayak | 15 | 5 |
| | | | | Garin Maji | 15 | 5 |
| | | Gamjam | Nasari | Garin Tsaiha | 15 | 5 |
| | | Lafiya Loiloi | Buduwa | Gamya | 15 | 5 |
| | **Sub-total** | **4** | **12** | **24** | **360** | **120** |
| Non-Beneficiary | *Spill-over* | | | | | |
| | Tarmuwa | – | – | Lantewa | – | 17 |
| | | – | – | Biriri | – | 17 |
| | Nangere | – | – | Dawasa | – | 17 |
| | | – | – | S/Gari Nangere | – | 17 |
| | Fune | – | – | Dogon Kuka | – | 17 |
| | | – | – | Damagum | – | 17 |
| | Fika | – | – | Janga | – | 18 |
| | | – | – | Gadaka | – | 18 |
| | **Sub-total** | **4** | – | **8** | – | **138** |
| | *Control* | | | | | |
| | Damaturu | – | – | Maisandari | – | 17 |
| | | – | – | Dukumari | – | 17 |
| | Gujba | – | – | Katarko | – | 17 |
| | | – | – | Kasesa | – | 17 |
| | Gulani | – | – | Bara | – | 17 |
| | | – | – | Shishiwaji | – | 17 |
| | Potiskum | – | – | Mamudo | – | 18 |
| | | – | – | Garin Jaji | – | 18 |
| | **Sub-total** | **4** | – | **8** | – | **138** |
| **Total** | **12** | **4** | **12** | **40** | | **396** |

*Source:* NEAZDP report (2022) and Reconnaissance survey (2022)

## 5.1 Empirical model

### 5.1.1 Economic/Income (unidimensional) approach of poverty measurement

**a. The decomposition of the FGT index across growth and redistribution effects**

Datt and Ravallion (1992) decompose the change in the FGT index between two periods, $t_1$ and $t_2$, into growth and redistribution components as follows (Urban et al., 2024; Rebechi and Rohde, 2023):

$$\mathrm{P}_2 - P_1 = [P(\mu^{t_2}, \pi^{t_1}) - P(\mu^{t_1}, \pi^{t_1})] + [P(\mu^{t_1}, \pi^{t_2}) - P(\mu^{t_1}, \pi^{t_1})] + R \quad /\mathrm{ref} = 1 \tag{2}$$

$$\mathrm{P}_2 - P_1 = [P(\mu^{t_2}, \pi^{t_2}) - P(\mu^{t_1}, \pi^{t_2})] + [P(\mu^{t_2}, \pi^{t_2}) - P(\mu^{t_2}, \pi^{t_1})] + R \quad /\mathrm{ref} = 2 \tag{3}$$

Where, $P_2 - P_1$ represents the difference (variation) in poverty between periods $t_1$ and $t_2$. Component 1 (C1) refers to the growth component or growth effect, whereas Component 2 (C2) denotes the redistribution component or redistribution effect. The term $R$ represents the residual component, and Ref. indicates the reference period.

$\boldsymbol{P(\mu^{t1}, \pi^{t1})}$: the FGT index of the first period.
$\boldsymbol{P(\mu^{t2}, \pi^{t2})}$: the FGT index of the second period.
$\boldsymbol{P(\mu^{t2}, \pi^{t1})}$: the FGT index of the first period when all incomes $y_i^{t1}$ are multiplied by $\mu^{t2}/\mu^{t1}$.
$\boldsymbol{P(\mu^{t1}, \pi^{t2})}$: the FGT index of the second period when all incomes $y_i^{t2}$ are multiplied by $\mu^{t1}/\mu^{t2}$.

The Shapley value decomposes the variation in the FGT Index between two periods, $t_1$ and $t_2$, into growth and redistribution components as follows (Aristondo and Onaindia, 2020; Fosu and Gafa, 2022):

$$P_2 - P_1 = C_1 + C_2 \tag{4}$$

$$C_1 = \frac{1}{2}\left([P(\mu^{t_2}, \pi^{t_1}) - P(\mu^{t_1}, \pi^{t_1})] + [P(\mu^{t_2}, \pi^{t_2}) - P(\mu^{t_1}, \pi^{t_2})]\right) \tag{5}$$

$$C_2 = \frac{1}{2}\left([P(\mu^{t_1}, \pi^{t_2}) - P(\mu^{t_1}, \pi^{t_1})] + [P(\mu^{t_2}, \pi^{t_2}) - P(\mu^{t_2}, \pi^{t_1})]\right) \tag{6}$$

**b. Pro-poor curves**

Pro-poor curves can be drawn using either the primal or the dual approach (Rehman et al., 2024; Fatima et al., 2024). The former uses income levels. The latter is based on percentiles.

The change in the distribution from state 1 to state 2 is s-order absolutely pro-poor with standard *cons* if:

$$\Delta(z, s) = (P_2(z + cons, \alpha = s - 1)) < 0 \quad \forall z \in [0, z^+] \tag{7}$$

The change in the distribution from state 1 to state 2 is s-order relatively pro-poor if:

$$\Delta(z, s) = (P_2(z + cons, \alpha = s - 1)) < 0 \quad \forall z \in [0, z^+] \tag{8}$$

## 5.2 Impact of demographic changes

This application computes the impact of a change (by a given percentage) in the proportion of a group $t$. That change is accompanied by an exact offsetting change in the proportion of the other groups (Ha, 2024; Septya et al., 2024).

If the population proportion of group $t$ increases by $pc$ percent, such that $\phi(t) \to (\phi(t)(1 + pc))$, the total estimated impact on poverty is as follows:

$$\Delta P = \left[\phi(t) * P(t; z, \alpha) - \sum_{k \neq t}^{K} \frac{\phi(t)}{1 - \phi(t)} * \phi(k) * P(k; z, \alpha)\right] * pc \tag{9}$$

If the population proportion of group $s$ increases by absolute $pc$ percent of the total population, such that $\phi(t) \to (\phi(t)(1+pc))$, the total estimated impact on poverty is as follows:

$$\Delta P = \left[P(t; z, \alpha) - \sum_{k \neq s}^{K} \frac{\phi(k)}{1 - \phi(t)} * P(k; z, \alpha)\right] * pc \tag{10}$$

Where $P(t;z,\alpha)$ is the FGT poverty index for subgroup $k$ and $\bar{\phi}(k)$ is the proportion of the population found in that subgroup.

## 5.3 FGT Poverty: decomposition by population subgroups

This decomposition takes the form:

$$\hat{P}(z;\alpha) = \sum_{g=1}^{G} \hat{\phi}(g)\hat{P}(z;\alpha;g) \tag{11}$$

Where $G$ denotes the number of population subgroups. The results provide the estimated FGT index for each subgroup $g$, $\hat{P}(z;\alpha;g)$, as well as the estimated population share of subgroup $g$, $\hat{\phi}(g)$. In addition, the absolute contribution of subgroup $g$ to total poverty is given by $\hat{\phi}(g)\hat{P}(z;\alpha;g)$, while its relative contribution to total poverty is computed as $(\hat{\phi}(g)\hat{P}(z;\alpha;g))/\hat{P}(z;\alpha)$.

## 5.4 Decomposition of change in FGT poverty by poverty and population group components – sectoral decomposition

Additive poverty measures, like the FGT indices (Ogwang and Mwabu, 2024; Bossert et al., 2022), can be expressed as a sum of the poverty contributions of the various subgroups of population (Bárcena-Martín and Cantó, 2025). Each subgroup contributes by its population share and poverty level. Thus, the change in poverty across time depends on the change in these two components. Denoting the population share of group $k$ in period 1 by $\phi_1(k)$, the change in poverty between two periods can be expressed as follows (Huppi and Ravallion, 1991; Duclos and Araar, 2006):

$$\begin{aligned} P_2 - P_1 = &\left[\sum_{k=1}^{K} \phi_1(k)(P_2(k;z;\alpha) - P_1(k;z;\alpha))\right] + \\ &\left[\sum_{k=1}^{K} P_1(k;z;\alpha)(\phi_2(k) - \phi_1(k))\right] + \\ &\left[\sum (P_2(k;z;\alpha) - P_1(k;z;\alpha))(\phi_2(k) - \phi_1(k))\right] \end{aligned} \tag{12}$$

Where $P_2 - P_1$ represents the change in poverty between periods 1 and 2. Component C1 captures the intra-sectoral or intra-group effects (i.e., changes occurring within the group itself), whereas C2 reflects the impact of changes in subgroup proportions, associated with demographic or sectoral shifts. Finally, C3 denotes the interaction effect.

This decomposition uses the initial period as the reference. If the reference period is the final one, the decomposition takes the form:

$$\begin{aligned} P_2 - P_1 = &\left[\sum_{k=1}^{K} \phi_2(k)(P_2(k;z;\alpha) - P_1(k;z;\alpha))\right] + \\ &\left[\sum_{k=1}^{K} P_2(k;z;\alpha)(\phi_1(k) - \phi_2(k))\right] + \\ &\left[\sum (P_2(k;z;\alpha) - P_1(k;z;\alpha))(\phi_1(k) - \phi_2(k))\right] \end{aligned} \tag{13}$$

To remove the arbitrariness in selecting the reference period, we can use the Shapley decomposition approach, finding:

$$\begin{aligned} P_2 - P_1 = &\left[\sum_{k=1}^{K} \bar{\phi}(k)(P_2(k;z;\alpha) - P_1(k;z;\alpha))\right] + \\ &\left[\sum_{k=1}^{K} \bar{P}(k;z;\alpha)(\phi_2(k) - \phi_1(k))\right] \end{aligned} \tag{14}$$

Where $\bar{\phi}(k)$ is the average population share $= 0.5(\phi_1(k) + \phi_2(k))$ and $\bar{P}(k;z;\alpha) = 0.5(P_1(k;z;\alpha) + P_2(k;z;\alpha))$.

## 5.5 Poverty dominance

Distribution 1 dominates distribution 2 at order $s$ over the conditional range $[Z^-, Z^+]$ if only:

$$P_1(\xi;\alpha) > P_2(\xi;\alpha) \quad \forall \xi \in [Z^-, Z^+] \quad \text{for } \alpha = s - 1 \tag{15}$$

This involves comparing stochastic dominance curves at order $s$ or FGT curves with $\alpha = s - 1$. This application checks for the points at which there is a reversal of the dominance conditions. Hence, it provides the crossing points of the dominance curves, i.e., the values of $\xi$ and $P_1(\xi;\alpha)$ for which $P_1(\xi;\alpha) = P_2(\xi;\alpha)$ when sign $(P_1(\xi-\eta;\alpha) - P_2(\xi-\eta;\alpha)) =$ sign $(P_2(\xi-\eta;\alpha) - P_1(\xi-\eta;\alpha))$ for a small $\eta$.

The crossing points of $\xi$ can also be referred to as "critical poverty lines".

### 5.6 Multidimensional poverty index (MPI)

The MPI is a composite indicator of poverty that accounts for both the distribution of deprived areas and their prevalence (Appendix 1) (Tigre, 2020; Sadıq and Sani, 2022; Salari et al., 2024). The following are the indexes involved in the measurement:

**Multidimensional headcount ratio (H):** Is the proportion of people who have been classified as multidimensionally poor, i.e., those who fall below the poverty line (Bhuiyan et al., 2023), and is expressed as:

$$H = q(k)/n \tag{16}$$

The number (or headcount) of multidimensionally poor people according to parameter $k$ is $q(k)$.

$$q(k) = \sum_{i=1}^{n} p_k(x_i; z) \tag{17}$$

The average deprivation share across the poor is defined as the intensity of poverty $A$, often known as the breadth of poverty (Marcelino and Cunha, 2023). This is presented as:

$$A = \sum_{i=1}^{q} C_i(k)/q(k) \tag{18}$$

The percentage of the $d$ indicators in which the average multidimensionally poor person is deprived is the intensity of poverty (Li and He, 2024).

The measure $M_0$ is the so-called adjusted headcount ratio when $\alpha = 0$.

$$M_0 = H \times A \tag{19}$$

When $\alpha = 1$, the measure $M_1$, adjusted poverty gap, defined as the weighted average of indicator-specific poverty gaps is used. $G$ is poverty gap.

$$M_1 = H \times A \times G \tag{20}$$

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{d} g_{ij}^{1}(k)}{\sum_{i=1}^{n} \sum_{j=1}^{d} g_{ij}^{0}(k)} \tag{21}$$

Finally, when $\alpha = 2$, the adjusted squared poverty gap ($M_2$) is calculated as the weighted average of the indicator-specific squared poverty gaps. $S$ is poverty severity.

$$M_2 = H \times A \times S \tag{22}$$

$$S = \frac{\sum_{i=1}^{n} \sum_{j=1}^{d} g_{ij}^{2}(k)}{\sum_{i=1}^{n} \sum_{j=1}^{d} g_{ij}^{0}(k)} \tag{23}$$

Seth and Alkire (2014) as reported by Sadıq and Sani (2022) suggested an additively decomposable inequality measure that is a positive multiple of "variance" and has within-group and between-group components. The inequality measure $I^q$ employs the vector of deprivation scores of the $q$ impoverished people $c_i(k)$ to quantify inequality among the poor at the national or sub-national level.

$$I^q = \frac{\tilde{\beta}}{q} \sum_{i=1}^{q} [c_i(k) - A]^2 \tag{24}$$

To calculate the measure of inequality, the difference between each poor person's deprivation score and average intensity is squared, then the squared distances are added together and multiplied by a constant $\tilde{\beta}$. We set $\tilde{\beta} = 1/49$ since the poor's deprivation ratings vary from $1/7$ to $1$. This is the greatest permissible number for the inequality gauge, guaranteeing that the inequality gauge is constrained between zero and one, given the spectrum of deprivation scores. Nevertheless, a lower degree of poverty or a decline in poverty does not necessarily mean that every region or demographic category has experienced an equal reduction in poverty (Sadıq and Sani, 2022; Sadiq and Grema, 2024; Sadiq et al., 2025).

# 6 Results and Discussion

## 6.1 The Role of NEAZDP on Social Mobility of Poverty among the Beneficiary Group

A perusal of Table 2 revealed the unidimensional social and economic mobility of poverty for the beneficiary group as the program transitioned through the initial period to the final period. The matrix showed that in the first quarter phase of the program, 24.17 % of the beneficiaries were significantly below the poverty threshold. Subsequently, as the program passed to the second quarter phase, the proportion of the beneficiaries below the poverty threshold significantly declined to 16.67 %. This significant reduction in the proportion of the beneficiaries that were below the poverty threshold persisted until the third quarter phase (15.83 %) of the program implementation.

Conversely, in the last (fourth-quarter) phase of the program implementation, there was a sudden reversal in the trend of poverty proportion (increase) among the beneficiaries in the study area, i.e., 20.83 % of the beneficiaries were significantly below the poverty threshold. The initial decline in poverty levels across the phases indicates positive economic mobility for the beneficiaries. They were initially moved towards improved economic conditions, potentially finding better employment opportunities or increasing their income through the program's support.

The increase in poverty levels in the last phase signifies a reversal in economic mobility. It could imply that the economic gains achieved earlier were not sustained or that external factors such as economic downturns, changes in policy, or programmatic issues have caused deterioration in economic status. Fluctuations in poverty levels can affect social stability. A sudden increase in poverty levels, as seen in the last phase, might lead to social unrest or dissatisfaction among beneficiaries. Therefore, policymakers should consider the factors that contributed to the increase in poverty in the last phase. This might involve addressing systemic issues, enhancing program monitoring and evaluation, or providing longer-term support to ensure sustained economic and social improvements.

In summary, while the NEAZDP program initially showed positive impacts on reducing poverty and enhancing mobility among beneficiaries, the increase in poverty levels in the last phase highlights challenges in achieving sustained social and economic mobility. Addressing these challenges is crucial for ensuring that interventions lead to lasting improvements in the lives of beneficiaries.

**Table 2.** Unidimensional social mobility of poverty for the beneficiary group

| | **Final period (AMI)** | | | | |
|---|---|---|---|---|---|
| **Initial period (BMI)** | **0.0 – 0.25** | **0.25 – 0.5** | **0.5 – 0.75** | **0.75 – 1.0** | **Total** |
| **0.0 – 0.25** | **0.241667**<br>**(-0.01342)**<br>**[-18.0073]**^ | 0.091667<br>(-0.01447)<br>[-6.33674]^ | 0.008333<br>(-0.00845)<br>[-0.9857]NS | 0.008333<br>(-0.00827)<br>[-1.00753]NS | 0.291667<br>(-3.6E-05)<br>[-8172.22]^ |
| **0.25 – 0.5** | 0.108333<br>(-0.0145)<br>[-7.46882]^ | **0.166667**<br>**(-0.01986)**<br>**[-8.39025]**^ | 0.091667<br>(-0.01846)<br>[-4.96439]^ | 0.041667<br>(-0.017)<br>[-2.45069]^ | 0.35<br>(-3.9E-05)<br>[-8995.12]^ |
| **0.5 – 0.75** | 0.008333<br>(-0.00815)<br>[-1.02304]NS | 0.15<br>(-0.01669)<br>[-8.98535]^ | **0.158333**<br>**(-0.02017)**<br>**[-7.85053]**^ | 0.058333<br>(-0.0151)<br>[-3.86247]^ | 0.333333<br>(-2.6E-05)<br>[-12679.1]^ |
| **0.75 – 1.0** | 0<br>(-0.00033)<br>[0]NS | 0.033333<br>(-0.00986)<br>[-3.3823]^ | 0.125<br>(-0.01581)<br>[-7.90809]^ | **0.208333**<br>**(-0.02311)**<br>**[-9.01317]**^ | 0.35<br>(-2.3E-05)<br>[-15125.3]^ |
| **Total** | 0.266667<br>(-3.1E-05)<br>[-8672.09]^ | 0.316667<br>(-2.5E-05)<br>[-12586.1]^ | 0.258333<br>(-3.9E-05)<br>[-6591.82]^ | 0.266667<br>(-2.8E-05)<br>[-9379.76]^ | 1<br>0<br>- |

*Note:* Values in ( ) and [ ] are standard errors and t-statistics, respectively; ^ & NS mean significant at 1 % and non-significant, respectively. Source: Field survey, 2023

## 6.2 Impact of Growth and Redistribution on Poverty of NEAZDP Beneficiaries

Furthermore, in assessing the effects of income growth and redistribution on poverty reduction among the beneficiary group (Table 3 and Figure 3), after program intervention, due to growth in the economy (i.e., economic growth), poverty declined by 6.20 %. Conversely, income redistribution increased poverty among the beneficiaries after program intervention, an indication of a poor system of tax administration; likewise, the social safety measure(s) are not pro-poor, i.e., they favor the non-poor against the poor in the beneficiary group.

Despite the program's impact on economic growth, the poor state of public expenditure (i.e., subsidies, social safety measures) and the presence of an ineffective progressive tax administration system constitute a clog in the wheel of the program's success and long-term sustainability in the study area. In other words, despite the NEAZDP's positive impact on economic growth and poverty reduction, the ineffective income redistribution, inadequate public expenditure, and flawed tax administration undermine its success and sustainability, necessitating targeted reforms in tax policy, public expenditure, and social safety measures to better support the poor.

Put differently, the results indicate that while NEAZDP-induced economic growth reduced poverty by 6.20 %, flawed income redistribution increased poverty among beneficiaries, highlighting issues in tax administration. This suggests that the benefits of economic growth are not reaching the poorest members of the community, potentially exacerbating inequality. For the NEAZDP to achieve its poverty reduction goals sustainably, it is crucial to reform tax policies to ensure a more equitable distribution of income, so that the poorest beneficiaries are effectively supported and can share in the program's benefits.

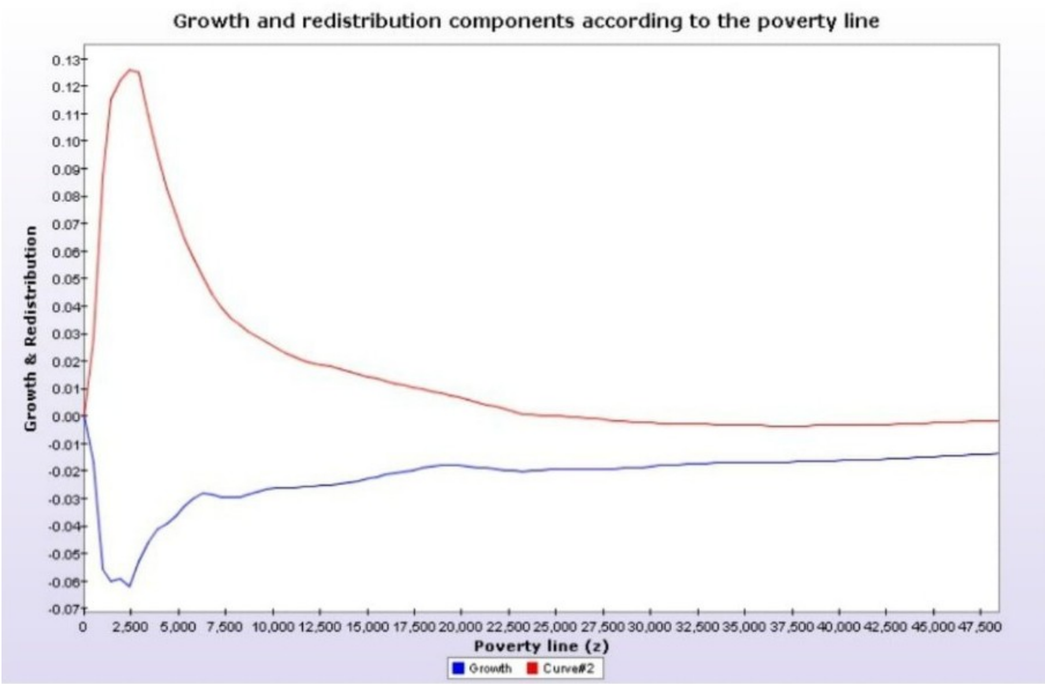



**Figure 3.** Growth and redistribution effects on poverty of NEAZDP

**Table 3.** Impact of growth and redistribution on poverty of the beneficiary group

| **I. Poverty indices** | | | |
|---|---|---|---|
| **Items** | **Initial** | **Final** | |
| **Reference 2** | | | |
| **Datt & Ravallion (1992) approach** | | | |
| Estimate | 0.36166427 (0.02728206) 13.2565*** | 0.42506710 (0.02850802) 14.9104*** | |
| Difference Index1–Index2 | 0.06340283 (0.03962348) 1.60013$^{NS}$ | | |
| Covariance Index1–Index2 | -0.00000650 | | |
| **Shapley approach** | | | |
| Estimate | 0.36166427 (0.02728206) 13.2565*** | 0.42506710 (0.02850802) 14.9104*** | |
| Difference Index1–Index2 | 0.06340283 (0.03962348) 1.60013$^{NS}$ | | |
| Covariance Index1–Index2 | -0.00000650 | | |
| **Reference 1** | | | |
| **Datt & Ravallion (1992) approach** | | | |
| Estimate | 0.36166427 (0.02728206) 13.2565*** | 0.42506710 (0.02850802) 14.9104*** | |
| Difference Index1–Index2 | 0.06340283 (0.03962348) 1.60013$^{NS}$ | | |
| Covariance Index1–Index2 | -0.00000650 | | |
| **Shapley approach** | | | |
| Estimate | 0.36166427 (0.02728206) 13.2565*** | 0.42506710 (0.02850802) 14.9104*** | |
| Difference Index1–Index2 | 0.06340283 (0.03962348) 1.60013$^{NS}$ | | |
| Covariance Index1–Index2 | -0.00000650 | | |
| **Poverty line** | 2417.78002930 (0.00000000) | | |
| **II. Decomposition (Contribution)** | | | |
| **Contribution of:** | **Growth** | **Redistribution** | **Residue** |
| | **Reference 2** | | |
| | -0.06196356 | 0.12571451 | -0.00034812 |
| | (0.06077006) | (0.12385039) | N.A |
| | 1.01964$^{NS}$ | 1.01505$^{NS}$ | – |
| | -0.06213762 | 0.12554045 | 0.00000000 |
| | (0.07908917) | (0.07908917) | (0.0) |
| **NEAZDP** | 0.785665$^{NS}$ | 1.58733$^{NS}$ | – |
| | **Reference 1** | | |
| | -0.06231168 | 0.12536639 | 0.00034812 |
| | (0.09838520) | (0.05125128) | N.A |
| | 0.633344$^{NS}$ | 2.44611** | – |
| | -0.06213762 | 0.12554045 | 0.00000000 |
| | (0.07908917) | (0.07908917) | (0.0) |
| | 0.785665$^{NS}$ | 1.58733$^{NS}$ | – |

*Note:* Values in parentheses ( ) are standard errors; ***, **, * and NS indicate statistical significance at the 1 %, 5 %, and 10 % levels, and non-significance, respectively. Source: Field survey, 2023

## 6.3 Pro-Poor Curve of NEAZDP Beneficiaries

Moreover, in assessing the pro-poor growth, after program participation, the results in Table 4 (depicted in Figure 4) showed a decline in the growth incidence (18.75 %) of poverty and a significant decline in the growth severity (17.22 %) of poverty. Succinctly, it can be inferred that the policies of the program directly targeted the poorest of the poor; in other words, the policies of the program are more generally aimed at poverty alleviation. Likewise, it can be concluded that the incomes of poor households in the beneficiary group grow faster than that of the whole population of the non-beneficiary group.

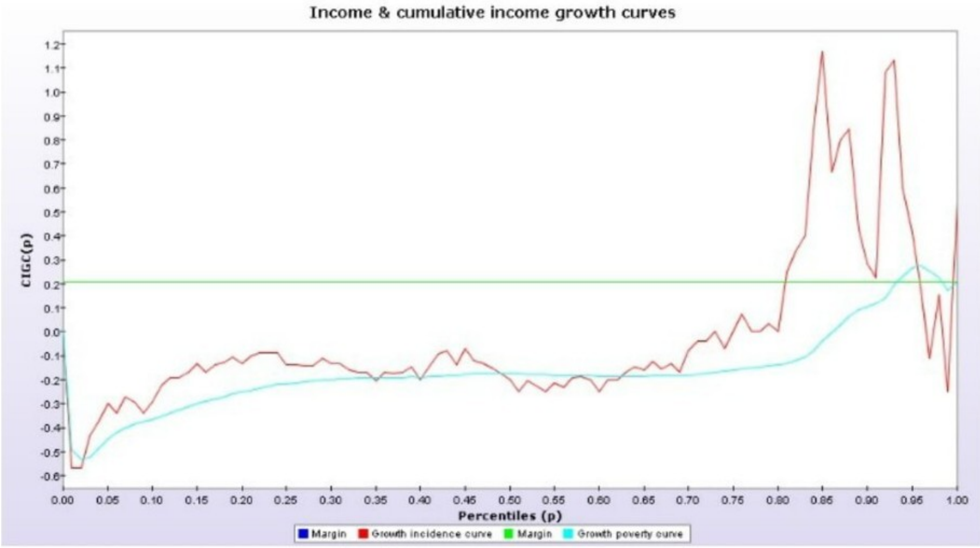



**Figure 4.** Pro-poor curve of the beneficiary group

**Table 4.** Pro-poor curve of beneficiary group

| Items | Estimated Value |
|---|---|
| Growth Incidence Curve | -0.18750001 (0.15652524) $1.19789^{NS}$ |
| Growth Poverty Curve | -0.17221867 (0.08624621) $1.996826^{**}$ |

*Note:* Value in ( ) is standard error; ***, **, * & NS mean significant at 1, 5, 10 % and non-significant respectively. Source: Field survey, 2023

Succinctly, for growth to be pro-poor, it means there is a fall in income inequality of the beneficiary group compared to the non-beneficiary group. Noteworthy, pro-poor growth is the type of growth that enables the poor to actively participate in economic activities and benefit proportionally more than the non-poor from overall income increase. This suggests that the program has effectively targeted and benefited the poorest individuals within the beneficiary group, leading to meaningful improvements in their living conditions. The significant decline in poverty severity also implies that the most vulnerable members are experiencing less extreme poverty, which is a positive outcome for long-term poverty reduction and improved well-being in the region.

In other words, the NEAZDP has effectively targeted the poorest households, leading to significant reductions in poverty incidence and severity, and ensuring that poor households benefit more proportionally from economic growth compared to the non-beneficiary group. Therefore, to enhance its impact, the program should continue focusing on equitable income growth and implement measures to further reduce income inequality.

## 6.4 Impact of Demographic Change on Poverty of NEAZDP Beneficiaries

In assessing the impact of demographics on poverty (relative to group) (Table 5), between beneficiary and spill-over groups respectively, for a 10 % change (increase) in the size of each group, poverty will significantly decline by 0.64 % and increase by 0.86 %, as evident by their respective impact coefficient at 10 % degree of freedom. Besides, the results showed a decrease (28.03 % to 26.21 %) in the proportion of poor in the beneficiary group against an increase (39.40 % to 43.34 %) in the proportion of poor in the spill-over group.

Moreover, relative to population, the results showed that a 10 % increase in each of the population of the beneficiary and spill-over groups, respectively, will significantly make poverty to decline and increase by 1.63 % and 2.18 %. On the other hand, relative to group, between beneficiary and control groups respectively, a 10 % increase in the size of each group will significantly plummet and increase poverty by 0.44 % and 1.63 %. Nevertheless, relative to population, for a 10 % increase in the group size of the beneficiary group, poverty will significantly plummet by 1.34 % whereas relative to the control group, poverty will significantly surge by 5.01 %.

**Table 5. Impact of demographic change on poverty**

| Items | Poverty Before | Poverty After | Total Impact |
|---|---|---|---|
| **Beneficiary vs. Spill-over** | | | |
| Relative to Group (RG) | 0.34835789 | 0.33988169 | -0.00847619 |
| | (0.07950081) | (0.08708012) | (0.01028815) |
| | 4.38182*** | 3.90309*** | $0.823879^{NS}$ |
| Relative to Population (RP) | 0.34835789 | 0.32684656 | -0.02151132 |
| | (0.07950081) | (0.06844059) | (0.00779362) |
| | 4.38182*** | 4.77562*** | 2.760119*** |
| **Poverty line** | | 11021.84 | |
| **Beneficiary vs. Control** | | | |
| Relative to Group (RG) | 0.33328196 | 0.34139459 | 0.00811263 |
| | (0.08290117) | (0.08831333) | (0.00637910) |
| | 4.02023*** | 3.86572*** | $1.27175^{NS}$ |
| Relative to Population (RP) | 0.33328196 | 0.35819332 | 0.02491135 |
| | (0.08290117) | (0.06957350) | (0.00721471) |
| | 4.02023*** | 5.14842*** | -3.45286*** |
| **Poverty line** | | 10733.72 | |
| **Beneficiary vs. Spill-over and Control** | | | |
| Relative to Group (RG) | 0.31974724 | 0.32697389 | 0.00722665 |
| | (0.07714256) | (0.08159047) | (0.00567126) |
| | 4.14489*** | 4.0075*** | $1.27426^{NS}$ |
| Relative to Population (RP) | 0.31974724 | 0.34193803 | 0.02219079 |
| | (0.07714256) | (0.06287188) | (0.00710749) |
| | 4.14489*** | 5.43865*** | 3.12217*** |
| **Poverty line** | | 10550.48 | |

**Table 5: Continued ....................**

| Group | Estimate | Proportion Before | Proportion After | Impact |
|---|---|---|---|---|
| | | **Beneficiary vs. Spill-over** | | |
| **1 (RG)** | 0.35214436 | 0.28030601 | 0.26207889 | -0.00641858 |
| | (0.05010282) | (0.33943272) | (0.33590802) | (0.00837355) |
| | 7.02843*** | 0.82581$^{NS}$ | 0.78021*** | 0.76653$^{NS}$ |
| **2** | 0.21800661 | 0.39403409 | 0.43343750 | 0.00859020 |
| | (0.00966169) | (0.38837504) | (0.42721254) | (0.00808642) |
| | 22.564*** | 1.01457$^{NS}$ | 1.01457$^{NS}$ | 1.0623$^{NS}$ |
| **1 (RP)** | 0.35214436 | 0.28030601 | 0.23404829 | -0.01628939 |
| | (0.05010282) | (0.33943272) | (0.30205948) | (0.01392726) |
| | 7.02843*** | 0.82581$^{NS}$ | 0.77484$^{NS}$ | 1.169605$^{NS}$ |
| **2** | 0.21800661 | 0.39403409 | 0.49403409 | 0.02180066 |
| | (0.00966169) | (0.38837504) | (0.38837504) | (0.00096617) |
| | 22.564*** | 1.01457$^{NS}$ | 1.27205$^{NS}$ | 22.564*** |
| | | **Beneficiary vs. Control** | | |
| **1 (RG)** | 0.32265320 | 0.28030601 | 0.26676916 | -0.00436771 |
| | (0.04848970) | (0.33943272) | (0.33022633) | (0.00669527) |
| | 6.65406*** | 0.82581*** | 0.80784$^{NS}$ | 0.652358$^{NS}$ |
| **3** | 0.50126922 | 0.32565993 | 0.35822592 | 0.01632433 |
| | (0.04570181) | (0.32955313) | (0.36250844) | (0.01503607) |
| | 10.9683*** | 0.98819$^{NS}$ | 0.98819$^{NS}$ | 1.08568$^{NS}$ |
| **1 (RP)** | 0.32265320 | 0.28030601 | 0.23873856 | -0.01341187 |
| | (0.04848970) | (0.33943272) | (0.29634706) | (0.01360754) |
| | 6.65406*** | 0.82581$^{NS}$ | 0.8056$^{NS}$ | 0.98562$^{NS}$ |
| **3** | 0.50126922 | 0.32565993 | 0.42565993 | 0.05012692 |
| | (0.04570181) | (0.32955313) | (0.32955313) | (0.00457018) |
| | 10.9683*** | 0.98819$^{NS}$ | 1.29163$^{NS}$ | 10.9683*** |
| | | **Beneficiary vs. Spill-over and Control** | | |
| **1 (RG)** | 0.32265320 | 0.28030601 | 0.26676916 | -0.00436771 |
| | (0.04848970) | (0.33943272) | (0.33022633) | (0.00669527) |
| | 6.65406*** | 0.82581$^{NS}$ | 0.80784$^{NS}$ | 0.652358$^{NS}$ |
| **2** | 0.19400491 | 0.39403409 | 0.37500495 | -0.00369175 |
| | (0.00931401) | (0.38837504) | (0.38642935) | (0.00458291) |
| | 20.8294*** | 1.01457$^{NS}$ | 0.97044$^{NS}$ | 0.805547$^{NS}$ |
| **3** | 0.46938863 | 0.32565993 | 0.35822592 | 0.01528611 |
| | (0.04114868) | (0.32955313) | (0.36250844) | (0.01413320) |
| | 11.4071*** | 0.98819$^{NS}$ | 0.98819$^{NS}$ | -1.08157$^{NS}$ |
| **1 (RP)** | 0.32265320 | 0.28030601 | 0.23873856 | -0.01341187 |
| | (0.04848970) | (0.33943272) | (0.29634706) | (0.01360754) |
| | 6.65406*** | 0.82581$^{NS}$ | 0.8056$^{NS}$ | 0.98562$^{NS}$ |
| **2** | 0.19400491 | 0.39403409 | 0.33560154 | -0.01133620 |
| | (0.00931401) | (0.38837504) | (0.34767237) | (0.00878248) |
| | 20.8294*** | 1.01457$^{NS}$ | 0.96528$^{NS}$ | 1.290774$^{NS}$ |
| **3** | 0.46938863 | 0.32565993 | 0.42565993 | 0.04693886 |
| | (0.04114868) | (0.32955313) | (0.32955313) | (0.00411487) |
| | 11.4071*** | -0.98819$^{NS}$ | 1.29163$^{NS}$ | 11.4071*** |

Source: Field survey, 2023

Note: Value in ( ) is standard error; ***, **, * & $^{NS}$ mean significant at 1, 5, 10 % and non-significant respectively; 1 = Beneficiary, 2 = Spillover, 3 = Control.

The NEAZDP has effectively reduced poverty among beneficiaries compared to the spill-over and control groups, with a 10 % increase in the beneficiary group size leading to a significant 1.34 % decrease in poverty. Therefore, to maximize impact, the program should focus on expanding its reach while ensuring effective measures are in place to prevent increasing poverty in control and spill-over groups.

Put differently, the results indicate that the NEAZDP effectively reduces poverty within the beneficiary group, with a 10 % increase in group size leading to a 1.34 % decrease in poverty. However, the spill-over and control groups experience rising poverty with similar population increases. This suggests the program is successfully targeting the beneficiary group but may be contributing to increased inequality and poverty in surrounding areas. To enhance overall impact, the program may need to extend benefits to spill-over and control groups or address the negative effects on these non-beneficiary groups.

Furthermore, in assessing poverty decomposition for two groups, between the beneficiary and spill-over groups (Table 6), the empirical evidence showed that 28.34 and 9.87 % of the significant 35.21 % who were poor among the beneficiary group were relatively poor (have basic needs but face social exclusion) and absolutely poor (lack basic needs), respectively. Contrarily, of the significant 21.80 % who were poor among the spill-over group, 8.59 % faced relative poverty while 24.66 % faced absolute poverty. Further, between the beneficiary and control groups, of the 32.27 % who were significantly poor among the former, 27.15 % are challenged with relative poverty whereas 9.04 % are challenged with absolute poverty. Contrarily, of the significant 50.13 % who were poor among the control group, 48.98 % were relatively poor while 16.32 % were absolutely poor.

Nevertheless, in assessing poverty decomposition by groups (a broader perspective, i.e., overall), between beneficiary against spill-over and control groups, it was observed that of the significant 32.27 % who were poor among the beneficiary group, 28.29 and 9.04 %, respectively, were relatively and absolutely poor. Contrarily, of the significant 19.40 % who were poor among the spill-over group, 23.91 and 7.65 %, respectively, were relatively and absolutely poor. Likewise, of the significant 46.94 % who were poor among the control group, 47.81 and 15.29 %, respectively, were relatively and absolutely poor.

**Table 6. FGT poverty decomposition (two groups and overall)**

| Items | Estimates |
|---|---|
| | **Beneficiary vs. Spill-over** |
| **Poverty line** | 11021.84 |
| Estimate | 0.34835789 (0.07950081) 4.38182*** |
| Abs. difference in contribution | 0.13413775 (0.05648720) 2.37466** |
| Difference in % in contribution | 0.03676145 (0.47523284) 0.07735$^{NS}$ |
| | **Beneficiary vs. Control** |
| **Poverty line** | 10733.72 |
| Estimate | 0.33328196 (0.08290117) 4.02023*** |
| Abs. difference in contribution | -0.17861602 (0.07945089) 2.248131** |
| Difference in % in contribution | -0.21843864 (0.57176186) 0.382045$^{NS}$ |
| | **Beneficiary vs. Spill-over and Control** |
| **Poverty Line** | 10550.48046875 (0.00000000) |
| Estimate | 0.31974724 (0.07714256) 4.14489*** |

**Table 6: Continued ....................**

| Group | Estimate | Population Share | Relative Contribution | Absolute Contribution |
|---|---|---|---|---|
| | | **Beneficiary vs. Spill-over** | | |
| **1** | 0.35214436 | 0.28030601 | 0.28335276 | 0.09870818 |
| | (0.05010282) | (0.33943272) | (0.30223390) | (0.10549074) |
| | 7.02843*** | 0.82581$^{NS}$ | 0.93753$^{NS}$ | 0.9357$^{NS}$ |
| **2** | 0.21800661 | 0.39403409 | 0.24659131 | 0.08590204 |
| | (0.00966169) | (0.38837504) | (0.28222683) | (0.08086418) |
| | 22.564*** | 1.01457$^{NS}$ | 0.87373$^{NS}$ | 1.0623$^{NS}$ |
| | | **Beneficiary vs. Control** | | |
| **1** | 0.32265320 | 0.28030601 | 0.27136672 | 0.09044163 |
| | (0.04848970) | (0.33943272) | (0.29265392) | (0.09593251) |
| | 6.65406*** | 0.82581$^{NS}$ | 0.92726$^{NS}$ | 0.94276$^{NS}$ |
| **3** | 0.50126922 | 0.32565993 | 0.48980537 | 0.16324329 |
| | (0.04570181) | (0.32955313) | (0.34020883) | (0.15036066) |
| | 10.9683*** | 0.98819$^{NS}$ | 1.43972$^{NS}$ | 1.08568$^{NS}$ |
| | | **Beneficiary vs. Spill-over and Control** | | |
| **1** | 0.32265320 | 0.28030601 | 0.28285351 | 0.09044163 |
| | (0.04848970) | (0.33943272) | (0.30035448) | (0.09593251) |
| | 6.65406*** | 0.82581$^{NS}$ | 0.94173$^{NS}$ | 0.94276$^{NS}$ |
| **2** | 0.19400491 | 0.39403409 | 0.23907804 | 0.07644454 |
| | (0.00931401) | (0.38837504) | (0.27542734) | (0.07167942) |
| | 20.8294*** | 1.01457$^{NS}$ | 0.86803$^{NS}$ | 1.06648$^{NS}$ |
| **3** | 0.46938863 | 0.32565993 | 0.47806844 | 0.15286106 |
| | (0.04114868) | (0.32955313) | (0.34060581) | (0.14133203) |
| | 11.4071*** | 0.98819$^{NS}$ | 1.40358$^{NS}$ | 1.08157$^{NS}$ |
| **Total** | — | 1.0 | 1.0 | 0.31974724 |
| | | (0.00) | (0.00) | (0.07714256) |
| | - | - | - | 4.14489*** |

Note: Value in ( ) is standard error; ***, **, * & $^{NS}$ mean significant at 1, 5, 10 % and non-significant respectively. Source: Field survey, 2023

The NEAZDP has been more successful in addressing absolute poverty among beneficiaries compared to the spill-over and control groups, significantly reducing absolute poverty while still encountering notable relative poverty. Thus, the program should continue focusing on reducing absolute poverty while also developing targeted interventions to address relative poverty and social exclusion. In other words, the results suggest that the NEAZDP has had a more substantial impact on reducing absolute poverty than relative poverty. The beneficiary group shows a higher proportion of individuals facing relative poverty compared to absolute poverty, indicating that while basic needs are generally met, issues of social exclusion persist. In contrast, both the spill-over and control groups experience higher rates of absolute poverty, especially the control group. This highlights the need for the NEAZDP to focus not only on reducing absolute poverty but also on addressing social exclusion and relative poverty to improve overall well-being.

Moreover, from a broader dimension, i.e., the sectoral decomposition of differences in poverty (natural), between the beneficiary versus the spill-over and control groups, the results showed a very drastic decline in the proportion of the beneficiary group that is challenged with absolute poverty against its counterparts in the spill-over and control groups (Table 7). Besides, due to program impact, as evident by the intra-group impact, the proportion of households in the beneficiary group that faces absolute poverty is 1.51 % against their counterparts in the spill-over group (2.40 %). Likewise, the proportion of households in the beneficiary group challenged with absolute poverty is 1.085 % against their counterparts in the control group (2.09 %). Generally, it can be inferred that program impact plays a great role in minimizing absolute poverty among the beneficiaries against their counterparts in the spill-over and control groups. Nevertheless, the results obtained under Shapley's decomposition model exhibited a similar trend. Conclusively, the NEAZDP has significantly reduced absolute poverty among beneficiaries compared to both spill-over and control groups, demonstrating its effectiveness in addressing severe poverty. Therefore, to enhance overall impact, the program should continue its focus on absolute poverty reduction while also exploring strategies to mitigate relative poverty and ensure broader social inclusion.

**Table 7.** FGT poverty decomposition (sectoral decomposition).

| Items | Distribution (1) | Distribution (2) | Difference P(2) - P(1) |
|---|---|---|---|
| | **Beneficiary vs. Spill-over** | | |
| | *Beneficiary* | *Spill-over* | |
| **Estimate (NA)** | 0.11783745 | 0.08572166 | -0.03211579 |
| | (0.03049792) | (0.02502065) | (0.00737291) |
| | 3.86379*** | 3.42604*** | 4.355918*** |
| **Estimate (SA)** | 0.11783745 | 0.08572166 | -0.03211579 |
| | (0.03049792) | (0.02502065) | (0.00737291) |
| | 3.86379*** | 3.42604*** | 4.355918*** |
| | **Beneficiary vs. Control** | | |
| | *Beneficiary* | *Control* | |
| **Estimate (NA)** | 0.11783745 | 0.07124325 | -0.04659420 |
| | (0.03049792) | (0.02222445) | (0.01077736) |
| | 3.86379*** | 3.20562*** | 4.323341*** |
| **Estimate (SA)** | 0.11783745 | 0.07124325 | -0.04659420 |
| | (0.03049792) | (0.02222445) | (0.01077736) |
| | 3.86379*** | 3.20562*** | 4.323341*** |

*Note:* Values in parentheses represent standard errors; ***, **, * and NS indicate statistical significance at the 1 %, 5 %, and 10 % levels, and non-significance, respectively. NA = Natural approach; SA = Shapley approach.
*Poverty line:* 11788.41.
*Source:* Field survey (2023).

**Table 7: Continued ........................................................**

| Group | Estimate (1) | Proportion (1) | Abs. Contribution (1) | Estimate (2) | Proportion (2) | Abs. Contribution (2) | Difference in Cont. (2)-(1) |
|---|---|---|---|---|---|---|---|
| 1 (NA) | 0.09089787 | 0.28030600 | 0.02547922 | 0.05386852 | 0.28030600 | 0.01509967 | -0.01037955 |
| | (0.01259371) | (0.33943273) | (0.02732501) | (0.00743065) | (0.33943273) | (0.01620270) | (0.01112231) |
| | 7.21772*** | 0.82581$^{NS}$ | 0.93245$^{NS}$ | 7.2495*** | 0.82581$^{NS}$ | 0.93192$^{NS}$ | 0.933219$^{NS}$ |
| 2 | 0.08015536 | 0.39403407 | 0.03158394 | 0.06097051 | 0.39403407 | 0.02402446 | -0.00755949 |
| | (0.00362057) | (0.38837504) | (0.02970480) | (0.00264210) | (0.38837504) | (0.02263913) | (0.00706566) |
| | 22.1389*** | 1.01457$^{NS}$ | 1.06326$^{NS}$ | 23.0765*** | 1.01457$^{NS}$ | 1.06119$^{NS}$ | 1.069892$^{NS}$ |
| 1 (SA) | 0.09089787 | 0.28030600 | 0.02547922 | 0.05386852 | 0.28030600 | 0.01509967 | -0.01037955 |
| | (0.01259371) | (0.33943273) | (0.02732501) | (0.00743065) | (0.33943273) | (0.01620270) | (0.01112231) |
| | 7.21772*** | 0.82581$^{NS}$ | 0.93245$^{NS}$ | 7.2495*** | 0.82581$^{NS}$ | 0.93192$^{NS}$ | 0.933219$^{NS}$ |
| 2 | 0.08015536 | 0.39403407 | 0.03158394 | 0.06097051 | 0.39403407 | 0.02402446 | -0.00755949 |
| | (0.00362057) | (0.38837504) | (0.02970480) | (0.00264210) | (0.38837504) | (0.02263913) | (0.00706566) |
| | 22.1389*** | 1.01457$^{NS}$ | 1.06326$^{NS}$ | 23.0765*** | 1.01457$^{NS}$ | 1.06119$^{NS}$ | 1.069892$^{NS}$ |
| 1 (NA) | 0.09089787 | 0.28030600 | 0.02547922 | 0.03868928 | 0.28030600 | 0.01084484 | -0.01463438 |
| | (0.01259371) | (0.33943273) | (0.02732501) | (0.00479623) | (0.33943273) | (0.01178852) | (0.01553649) |
| | 7.21772*** | 0.82581$^{NS}$ | 0.93245$^{NS}$ | 8.0666*** | 0.82581$^{NS}$ | 0.91995$^{NS}$ | 0.941936$^{NS}$ |
| 3 | 0.18661886 | 0.32565992 | 0.06077428 | 0.12230989 | 0.32565992 | 0.03983143 | -0.02094285 |
| | (0.01677674) | (0.32955313) | (0.05605531) | (0.01162652) | (0.32955313) | (0.03653385) | (0.01952147) |
| | 11.1237*** | 0.98819$^{NS}$ | 1.08418$^{NS}$ | 10.5199*** | 0.98819$^{NS}$ | 1.09026$^{NS}$ | 1.072811$^{NS}$ |
| 1 (SA) | 0.09089787 | 0.28030600 | 0.02547922 | 0.03868928 | 0.28030600 | 0.01084484 | -0.01463438 |
| | (0.01259371) | (0.33943273) | (0.02732501) | (0.00479623) | (0.33943273) | (0.01178852) | (0.01553649) |
| | 7.21772*** | 0.82581$^{NS}$ | 0.93245$^{NS}$ | 8.0666*** | 0.82581$^{NS}$ | 0.91995$^{NS}$ | 0.941936$^{NS}$ |
| 3 | 0.18661886 | 0.32565992 | 0.06077428 | 0.12230989 | 0.32565992 | 0.03983143 | -0.02094285 |
| | (0.01677674) | (0.32955313) | (0.05605531) | (0.01162652) | (0.32955313) | (0.03653385) | (0.01952147) |
| | 11.1237*** | 0.98819$^{NS}$ | 1.08418$^{NS}$ | 10.5199*** | 0.98819$^{NS}$ | 1.09026$^{NS}$ | 1.072811$^{NS}$ |

Source: Field survey, 2023

Poverty line = 11788.41

## 6.5 Poverty Dominance (Beneficiary versus Spill-over and Control Groups)

In assessing the poverty dominance between the beneficiary and spill-over groups, the results showed poverty to dominate in the spill-over group against the beneficiary group (Table 8). At cross 1 (case #1), the poverty crossing value for the beneficiary group out of the critical relative poverty line is ₦7,647.18, whereas the relative poverty crossing point for the spill-over group is ₦7,657.59 at cross 2 (case #2). Likewise, at cross 3 (case #2), the significant amount needed by the beneficiary group to cross over the line of relative poverty is ₦8,057.53, while the spill-over group needs a significant amount in the sum of ₦14,113.54 to cross over the relative poverty line at cross 4 (case #2). Comparatively, the margin of cross-over between the two groups is slight at cross 1 versus 2, while it is wide at cross 3 (case #1) versus cross 4 (case #2).

On the other hand, between the beneficiary and control groups, the poverty dominance of the latter is higher than that of the former as evident by case #1 versus case #2. Besides, the poverty crossing value of the beneficiary group is ₦46,296.82 against that of the control group (₦53,709.65). It is noteworthy that the poverty crossing values of both groups were significant thresholds; however, the marginal difference between the thresholds of the duo is mild.

The NEAZDP has effectively reduced poverty compared to the spill-over and control groups, with beneficiaries requiring significantly less to cross the relative poverty line, indicating better poverty alleviation. To further enhance its impact, the program should focus on deepening its interventions to address the remaining poverty gaps and reduce the disparities within the control group. In other words, the results indicate that while the NEAZDP has been somewhat effective, poverty remains more dominant in the spill-over group compared to the beneficiary group. The beneficiary group requires a smaller amount to move out of relative poverty compared to the spill-over group, but a larger amount compared to the control group. The control group faces higher poverty dominance overall. These findings suggest that the NEAZDP is moderately successful in reducing poverty but highlights the need for more targeted interventions to address the wider poverty gap and improve the situation of both spill-over and control groups.

**Table 8.** Poverty dominance between beneficiary vs. spill-over and control groups

| Crossing | Value of Z | Standard Error | t-statistic | Case |
|---|---|---|---|---|
| **Beneficiary vs. Spill-over** | | | | |
| 1 | 7647.18310547 | 157.33786159 | 48.60358 | 1 |
| 2 | 7657.59179688 | 156.71906348 | 48.8619 | 2 |
| 3 | 8057.53173828 | 254.47420782 | 31.66345 | 1 |
| 4 | 14113.53808594 | 665.59058712 | 21.20453 | 2 |
| **Beneficiary vs. Control** | | | | |
| 1 | 46296.81640625 | 409.09327366 | 113.1693 | 1 |
| 2 | 53709.64843750 | 6245.16691867 | 8.600194 | 2 |

*Source:* Field survey, 2023.
*Note:* Case #1 = Before, Distribution #1 Dominates Distribution #2; Case #2 = Before, Distribution #2 Dominates Distribution #1.

## The Role of NEAZDP on Multidimensional Poverty Status of the Beneficiary against the Spill-over and Control Groups

A cursory review of the multidimensional poverty level showed that at the poverty threshold level ($k = 0.33$), a proportion of 28.21 % of the households in the beneficiary group were multidimensionally poor against that of the spill-over (61.51 %) and control (52.99 %) groups as indicated by their respective head count ratio index (Table 9 and Figure 5a). Comparatively, the incidence of poverty is low among the beneficiaries compared to the non-beneficiary group: the states of acute poverty in the spill-over and control groups are higher than that of the beneficiary group by 33.3 % and 24.78 %, respectively. This suggests that the intervention has been effective in reducing poverty among beneficiaries.

Besides, the average poor household of the beneficiary group is deprived of 36.64 % of the weighted indicators against that of the spill-over and control groups respectively that are deprived of 40.19 % and 38.68 % of the weighted indicators as evident by their respective intensity poverty index. Succinctly, the poor households in the beneficiary group experienced 10.34 % deprivation out of the total potential deprivations that could be experienced compared to the poor households in the spill-over and control groups respectively that experienced deprived share proportions of 24.72 % and 20.49 % from the total potential deprivation as evident from their respective MPI (multidimensional poverty index).

Nevertheless, as evident by the MPG (multidimensional poverty gap) index, the average indicator-specific gap between haves and non-haves of the beneficiary group is 17.87 % against that of the spill-over and control groups respectively that were 36.79 % and 32.49 %. By implication, if the poor households in the beneficiary, spill-over and control groups respectively become more deprived in the challenged indicator(s), poverty would surge by 17.87 %, 36.79 % and 32.49 %. Similarly, if the shortfall from the deprivation cutoff is reduced, the poverty levels of the beneficiary, spill-over and control groups respectively will go down by 17.87 %, 36.79 % and 32.49 %, even if a poor household remains poor. Besides, the average severity of the deprived indicator(s) for the beneficiary, spill-over and control groups were 11.34 %, 22.12 % and 20 % respectively as evident by their respective MPS (multidimensional poverty severity) indexes.

To sum up, the share contribution of the beneficiary group to poverty in the study area is 17 % against that of the spill-over (45 %) and control (38 %) groups. In the same vein, the share poverty population of the beneficiary group is 30.38 % compared to that of the spill-over (34.68 %) and control (34.94 %) groups. Nevertheless, among the poor households in the beneficiary group, standard of living ranked first as the major deprived indicator, followed by empowerment and then environment as evident in the dimension-wise distribution (Figures 5b and 5c). Comparatively, the contribution of groups to poverty exceeds that of the groups' poverty population share (Figure 5d). By implication, it entails that there is no serious unequal distribution of poverty within the beneficiary group while the reverse is the case for the spill-over and control (non-beneficiary) groups bearing a disproportionate share of poverty for each group. In addition, inequality in the poverty level of poor households across the targeted populations was low as evident by the inequality index value. However, according to Alkire and Foster (2011), as reported by Sadıq and Sani (2022); Sadiq and Grema (2024), a lower level of inequality among the poor or a drop in the degree of inequality among the poor does not always imply that poverty has decreased uniformly across demographic subgroups.

Noteworthy, the case of a severe poverty level ($k = 0.50$) was not established across the targeted groups. Generally, it can be inferred that the NEAZDP beneficiaries in the study area experienced lower multidimensional poverty compared to spill-over and control groups, with lower incidence, intensity, and severity of poverty. Despite these improvements, challenges remain in specific dimensions like standard of living, empowerment, and environment. The program's success in reducing poverty shares and severity underscores its potential to alleviate poverty further if targeted indicators are addressed. Effective policy adjustments could enhance impact, potentially reducing poverty by up to 17.87 % among beneficiaries. These findings underscore the program's positive impact while emphasizing areas for continued improvement and focused intervention.

**Table 9.** MPI distributions of beneficiary vis-à-vis spill-over and control groups

| **Items** | **Beneficiaries** | **Spill-over** | **Control** |
|---|---|---|---|
| Head count (H) | 0.282086 | 0.615061 | 0.529859 |
| Intensity (A) | 0.366389 | 0.401897 | 0.386753 |
| MPI | 0.103353 | 0.247191 | 0.204925 |
| Gap | 1.729339 | 1.488198 | 1.585633 |
| MPG | 0.178732 | 0.367869 | 0.324935 |
| Severity (S) | 1.097565 | 0.895027 | 0.975874 |
| MPS | 0.113437 | 0.221243 | 0.199981 |
| Inequality (IE) | 3.21E-05 | 9.44E-05 | 6.43E-05 |
| CG | 17 | 45 | 38 |
| PS | 30.38 | 34.68 | 34.94 |
| **Dimension** | | | |
| Education (E) | 0.008952 (8.662) | 0.015704 (6.352877) | 0.019007 (9.275217) |
| Health (H) | 0.009 (8.708198) | 0.020142 (8.148421) | 0.020157 (9.836424) |
| Standard Living | 0.025337 (24.51539) | 0.058761 (23.77151) | 0.04826 (23.55028) |
| Environment (EN) | 0.018764 (18.15555) | 0.028173 (11.39714) | 0.034167 (16.67294) |
| Empowerment (EM) | 0.019778 (19.13596) | 0.036744 (14.8648) | 0.026848 (13.10163) |
| Social capital (S) | 0.008817 (8.531108) | 0.043181 (17.46851) | 0.020548 (10.02689) |
| Wealth (W) | 0.012704 (12.29179) | 0.044486 (17.99674) | 0.035937 (17.53662) |
| MPI | 0.103352 (100) | 0.247191 (100) | 0.204924 (100) |

*Source:* Field survey, 2023.
*Note:* Value in ( ) is percentage; CG = contribution of group; PS = population share; Standard of living (SL).

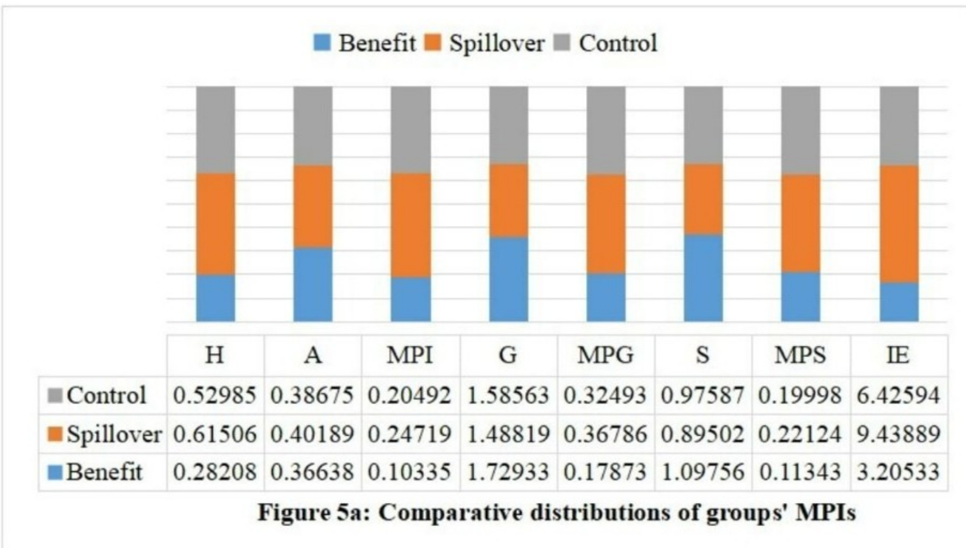
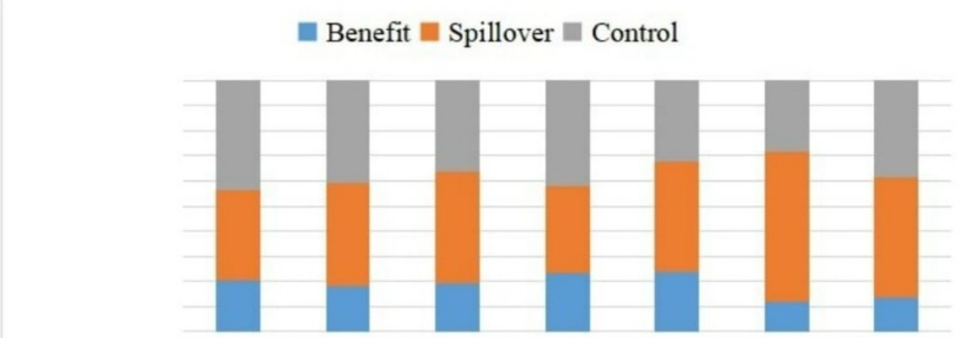


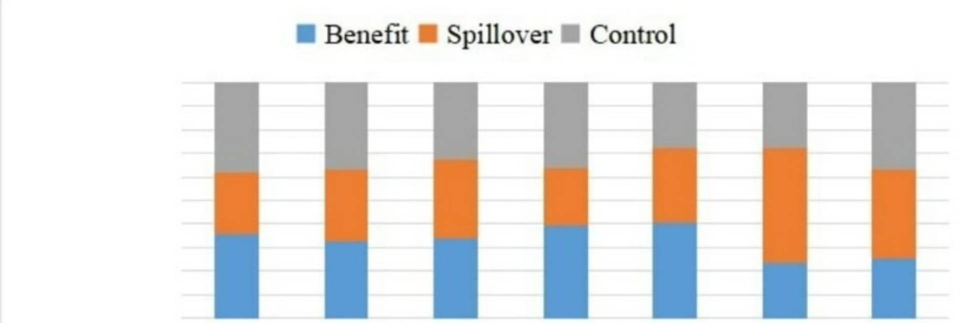

**Figure 5a.** Comparative distributions of groups' MPIs




| | ED | H | SL | EN | EM | SC | W |
|---|---|---|---|---|---|---|---|
| Control | 0.01900 | 0.02015 | 0.04826 | 0.03416 | 0.02684 | 0.02054 | 0.03593 |
| Spillover | 0.01570 | 0.02014 | 0.05876 | 0.02817 | 0.03674 | 0.04318 | 0.04448 |
| Benefit | 0.00895 | 0.00900 | 0.02533 | 0.01876 | 0.01977 | 0.00881 | 0.01270 |

**Figure 5b: Index comparative distributions of groups' dimensions to MPI**

**Figure 5b.** Index comparative distributions of groups' dimensions to MPI




| | ED | H | SL | EN | EM | SC | W |
|---|---|---|---|---|---|---|---|
| Control | 9.27521 | 9.83642 | 23.5502 | 16.6729 | 13.1016 | 10.0268 | 17.5366 |
| Spillover | 6.35287 | 8.14842 | 23.7715 | 11.3971 | 14.8648 | 17.4685 | 17.9967 |
| Benefit | 8.66200 | 8.70819 | 24.5153 | 18.1555 | 19.1359 | 8.53110 | 12.2917 |

**Figure 5c: % comparative distributions of groups' dimension**

**Figure 5c.** % comparative distributions of groups' dimension

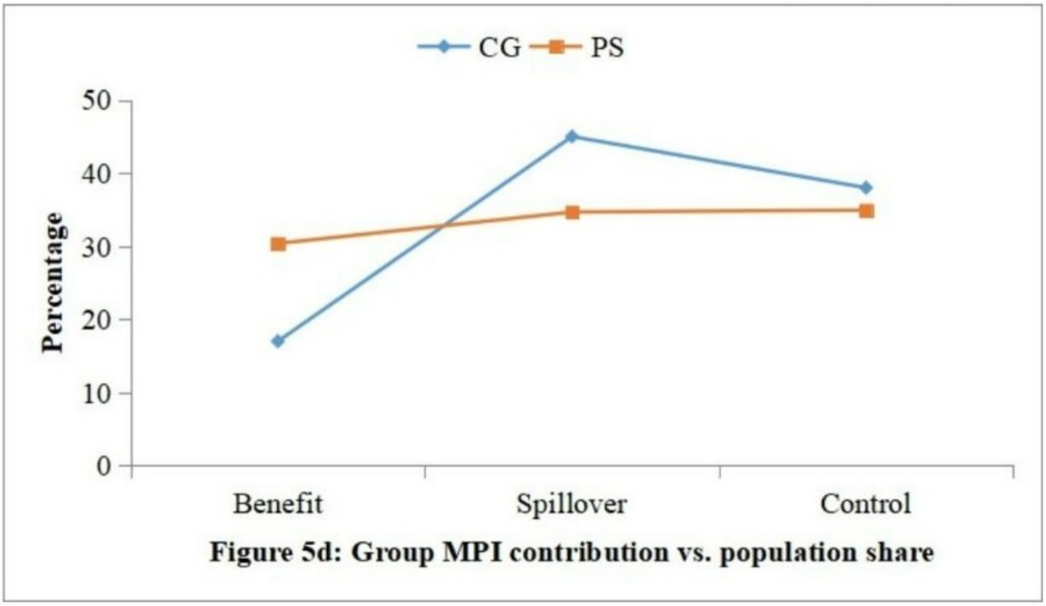



**Figure 5d.** Group MPI contribution vs. population share

## Conclusions and Recommendations

The Northeast Arid Zone Development Program (NEAZDP) has shown significant effectiveness in reducing poverty among beneficiaries in Yobe State. The study reveals a consistent decline in the proportion of beneficiaries below the poverty threshold over time, with a notable improvement observed until the third quarter phase of the program. The program has successfully reduced the incidence, intensity, and severity of poverty among its participants, particularly in dimensions related to standard of living, empowerment, and environment. Despite improvements, challenges persist in specific dimensions of poverty, highlighting the need for targeted interventions. Inequality within the beneficiary group remains low, but disparities are evident between beneficiaries and non-beneficiaries, emphasizing the importance of equitable distribution and inclusive growth strategies. Consequently, the present study offered the following recommendations for inclusivity and comprehensive growth among the beneficiaries in the study area:

It is imperative for the program to focus on addressing specific dimensions of poverty identified in the study, particularly improving quality education, healthcare, and sustainable livelihoods.

The program should strengthen environmental conservation efforts and promote sustainable agricultural practices to ensure long-term resilience and reduce vulnerability to climate risks.

The program should implement rigorous monitoring mechanisms to track poverty reduction indicators continuously and adjust programs based on real-time data.

The program should integrate poverty alleviation strategies with broader development policies at local, regional, and national levels to ensure comprehensive and inclusive growth (i.e., inclusivity and equity in resource distribution).

The program advises investing in capacity-building initiatives to empower local communities and institutions to sustain poverty reduction efforts independently.

## Authors' contributions

**M.S.S.:** Conceptualization, data processing, results and discussion (60 %). **I.J.G.:** Introduction, methodology, results and discussion (40 %).

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# Appendix

**Appendix 1:** Dimensions, indicators, cut-off points and relative weight (RW) of MPI

| Dimensions | Indicators | Deprivation cut-off | RW |
|---|---|---|---|
| **Education** | School | No child ($\geq 10$ years) has completed five years of schooling. | 1/28 |
| | School | No school age child (1–6 years) is attending school. | 1/28 |
| | Literacy | The primary household has no formal education. | 1/28 |
| | Literacy | The secondary household head has no formal education. | 1/28 |
| **Health** | Nutrition | Any family member that is underweight (slim) (BMI $< 18.5$) or overweight ($\geq 23$) / obesity ($\geq 25$). | 1/28 |
| | Immunization | Any family member not immunized/vaccinated to prevent any type of communicable diseases. | 1/28 |
| | Ante-natal care | Any pregnant women in the household with less than four (4) antenatal care. | 1/28 |
| | Morbidity | Any household member being sick in the last 5 months prior to survey. | 1/28 |
| **Standard of living** | Housing | Household living in an inadequate housing condition. | 1/63 |
| | Insurance | No family member is insured under any type of health insurance scheme. | 1/63 |
| | Electricity | No access to electricity. | 1/63 |
| | Water | No access to safe drinking water. | 1/63 |
| | Mobility | Doesn't own any type of motor vehicle for transportation purpose. | 1/63 |
| | Financial institution | Doesn't possess a savings bank account. | 1/63 |
| | Residential plot | Doesn't own any $100m^2$ of residential land other than where he/she is residing. | 1/63 |
| | Food security | Household is below food security threshold (2/3 of food expenditure). | 1/63 |
| | Over population | Household is overcrowded. | 1/63 |
| **Empowerment** | Health decision | Unable to take healthcare decision. | 1/63 |
| | Domestic violence | Unable to prevent domestic violence. | 1/63 |
| | Instability | Problem of social/political unrest. | 1/63 |
| | Self-defense | Problem of personal security. | 1/63 |
| | Job | Doesn't take any type of employment decision(s) for himself other than farming activities. | 1/63 |
| | Diversification | Doesn't participate in off-farm activities. | 1/63 |
| | Credit | No access to credit facilities in the last production season prior to the survey. | 1/63 |
| | Facilities | Doesn't belong to any co-operative organisation. | 1/63 |
| | Advisory services | Doesn't have access to extension service in the last production season prior to the survey. | 1/63 |
| **Environment** | Toilet | Household still practicing open defecation. | 1/14 |
| | Energy | Using dirty fuel as primary energy for cooking (e.g. firewood, dung & charcoal). | 1/14 |
| **Social connection** | Community service | Household head has not participated in any type of community-level activities. | 1/21 |
| | Co-operate responsibility | The household has not been involved in organizing any type of community-level activities. | 1/21 |

Continued on next page...

**Appendix 1: Continued**

| Dimensions | Indicators | Deprivation cut-off | RW |
|---|---|---|---|
| | Social safety net | Doesn't trust government social investment programme (e.g. farmers/traders monie etc.). | 1/21 |
| **Wealth** | Agricultural land | Household doesn't own any agricultural land. | 1/28 |
| | Livestock | Livestock ownership (deprived if TLU is less than average). | 1/28 |
| | Dead stock (agric.) | Doesn't possess agricultural dead stocks. | 1/28 |
| | Dead stock (non-agric.) | Doesn't possess non-agricultural dead stocks. | 1/28 |

*Source:* Modified from Sadıq and Sani (2022); Sadiq and Grema (2024); Sadiq et al. (2024).

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Quality of life and sustainability



# Development of an Instrument Based on the EGCI Model to Measure Sustainable Water Use Practices among Citizens

# Construcción de un instrumento basado en el modelo EGCI para medir prácticas sostenibles de uso del agua en la ciudadanía

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**Abstract**

At present, residential water conservation behaviors are essential to prevent the growing global scarcity of water resources. This study aims to analyze the factors that influence citizens' intention to adopt sustainable water care practices, integrating the variables of the EGCI model under a responsible consumption perspective. To this end, an online survey was conducted with 450 participants in Mexico, one of the countries facing a severe water crisis. The instrument was specifically designed for this study, taking into account relevant variables associated with the EGCI acronym (Economic consumption, Sustainable water management, Moral commitment, and Intention to adopt sustainable practices). Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The results show that moral commitment has a direct and positive influence on both sustainable water management and the intention to implement responsible practices. Likewise, it was confirmed that the perception of reduced costs associated with water consumption has a direct and positive impact on more efficient water management. These findings highlight the importance of continuing to educate citizens not only about responsible water savings but also about offering alternatives for the sustainable management of this resource. Furthermore, they support the design of targeted campaigns aimed at different sectors of society to modify consumption patterns, as well as the use of technological tools to reduce waste and improve water-use efficiency.

***Keywords***: Consumer economics, sustainable water management, moral commitment, intention to adopt sustainable practices.

**Resumen**

En la actualidad, las conductas de conservación del agua en el ámbito residencial son esenciales para prevenir la creciente escasez global del recurso hídrico. Este estudio tiene como objetivo analizar los factores que influyen en la intención de la ciudadanía de adoptar prácticas sostenibles de cuidado del agua, integrando las variables del modelo EGCI bajo una perspectiva de consumo responsable. Para ello, se aplicó una encuesta en línea a 450 personas en México, uno de los países que enfrenta una crisis hídrica severa. El instrumento fue diseñado específicamente para este estudio, considerando variables relevantes asociadas al acrónimo EGCI (Economía del consumo, Gestión sostenible del agua, Compromiso moral, Intención de prácticas sostenibles). Los datos fueron analizados mediante modelos de ecuaciones estructurales con mínimos cuadrados parciales (PLS-SEM). Los resultados evidencian que el compromiso moral influye de manera directa y positiva tanto en la gestión sostenible del agua como en la intención de implementar prácticas responsables. Asimismo, se comprobó que la percepción de reducción de costos asociados al consumo hídrico incide positivamente en una gestión más eficiente. Estos hallazgos subrayan la necesidad de continuar promoviendo la educación ciudadana en torno al ahorro responsable y la gestión sostenible del agua, además de diseñar campañas segmentadas que transformen patrones de consumo y fomenten el uso de tecnologías orientadas a minimizar el desperdicio y mejorar la eficiencia en el uso del recurso.

***Palabras clave***: Economía del consumo, gestión sostenible del agua, compromiso moral, intención de prácticas sostenibles.

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# 1 Introduction

It is well known that "Day Zero" is associated with a future in which water scarcity will be irreversible; however, the reality is that this scenario is already affecting several regions of the Mexican Republic (Coparmex, 2024). This is due to a series of factors, among which climate change, poor metropolitan planning (Gómez, 2024), and the inadequate use of resources by the population (Gaspar-Santos et al., 2024) can be mentioned.

For this reason, the present research focuses on Sustainable Development Goal (SDG) 6, "Clean Water and Sanitation," which guarantees access to safe drinking water and its sustainable management; since it is estimated that by 2030 billions of people will not have access to this resource unless the population is educated on the efficient use of this valuable water resource, as well as through increased investment in water and sanitation infrastructure and facilities (Organización de las Naciones Unidas, 2020).

Furthermore, the problem of water scarcity is not only of national but also of international concern, because access to this vital resource represents a challenge, as water is sometimes contaminated by high levels of salinity, nitrate, and chloride (AlHaddid et al., 2024; Salem and Ertz, 2023). Indeed, in 2023 water scarcity affected more than 2 billion people worldwide, and this number is expected to increase in the coming years, causing food insecurity, the extinction of some species, droughts that threaten human life, and conflicts between governments over water resources (Nasiri et al., 2024).

According to the National Water Commission (CONAGUA), the state of Puebla ranked second nationwide with the highest level of drought in 2024, due to insufficient rainfall to supply the territory (Milenio, 2024). As a result, the population was advised to recycle water to irrigate plants, wash vehicles, or flush toilets; in addition, citizens were encouraged to avoid littering the streets in order to prevent the clogging of drainage systems and storm drains.

It is important to note that, due to the increasing scarcity of water, there has been a push to seek innovative and sustainable solutions for water management in Puebla; for example, the use of greywater in households has been proposed as a strategy to reduce water consumption, along with modifications to existing plumbing and the installation of an underground storage tank (Reynoso Castro and Díaz Barrientos, 2024). In addition, the right to water is indispensable, even though climate change has caused extreme alterations in climatic conditions that have directly affected the availability of freshwater; for example, rising temperatures lead to intense droughts in some regions by evaporating water from surface water bodies. Therefore, the participation of both citizens and governments is necessary to prevent the scarcity of this vital resource (Rodriguez Garcia, 2024).

According to Gaspar-Santos et al. (2024), proper sustainable water management is crucial to protect the environment and ensure the provision of water resources for future generations. Therefore, the objective of the present study is to analyze the factors that influence citizens' intention to adopt sustainable water-care practices, integrating the variables of the EGCI model from a responsible consumption perspective. The results of the study identify opportunities to improve water-use efficiency, as well as to serve as a reference for predictive models of population behavior regarding the sustainable use of natural resources.

# 2 Theoretical framework

Previous literature has indicated that behavior aimed at predicting water consumption by the population does not depend solely on external factors, such as price or distribution, availability of information on water-saving measures, among others; but also on personal conditions and the motivational forces of the decision-maker (Cary, 2008; Pino et al., 2017). Therefore, for the purposes of the present research, variables studied in the context of water conservation, such as consumption economics and sustainable water management (Chenoweth et al., 2016; Lowe et al., 2015; Salem and Ertz, 2023), are considered, as well as variables related to environmental awareness and moral commitment, which have been addressed in studies on environmental protection (Imani et al., 2021; Keles et al., 2023; Rusyani et al., 2021), and finally, the variable of intention to adopt sustainable practices in water conservation (Fatoki, 2022; Lowe et al., 2015; Mitev et al., 2024; Salem and Ertz, 2023).

## 2.1 Sustainable water management for Social Responsibility

According to Chenoweth et al. (2016), the proper use of water is essential to reduce pressure on water sources and the environment. Indeed, the effective management of this vital resource is a priority for many countries worldwide due to industrialization and urbanization processes, which lead to excessive and unplanned water consumption (Pino et al., 2017). For their part, Mitev et al. (2024) state that reducing household water demand is an essential component of reducing overall water consumption in large cities. Indeed, governments, investors, the public, and market forces such as consumers are the driving forces that promote water conservation (Zhang et al., 2025). For example, water supply companies provide users with information on how to improve water consumption and savings through various media channels (Tian and Chen, 2022).

However, Beal et al. (2013) and Tian and Chen (2022) argue that even when households are aware of how to manage water and are conscious of the problem of scarcity, their water-saving behaviors are not the most effective, negatively impacting social responsibility.

## 2.2 Intention to adopt sustainable practices

Regarding individuals' intention to save water, climate change mitigation and resilience building require a multidimensional approach that combines the modification of personal habits, such as reducing shower time and collecting rainwater, with the adoption of efficient infrastructure through the use of water-saving products (Mitev et al., 2024; Muenratch and Nguyen, 2023; Guo et al., 2022; Djayasinga, 2021). In addition, the intention to adopt sustainable practices may manifest in various areas, such as responsible consumption, sustainable mobility, waste management, conservation of natural resources (Lowe et al., 2015), and electricity savings (Fatoki, 2022).

According to Truong (2024), individuals' intention refers to their willingness to purchase or adopt products based on personal experiences, relying on internal aspects (emotions) or external aspects (cost–benefit relationships). In the same vein, AlHaddid et al. (2024) state that adopting sustainable water-related practices at the household level is hindered by the intention–behavior gap; in other words, the difference between observed or desired practices and actual practices at the household level.

## 2.3 Consumption economics and sustainable water management

Within the field of water economics, Mitev et al. (2024) and Muenratch and Nguyen (2023) argue that resource conservation is essential to mitigate climate change and strengthen the resilience of supply systems. However, they warn that the effectiveness of these strategies faces the barrier of excessive consumption habits, which are so deeply rooted that they hinder the adoption of new conservation behaviors, such as greywater reuse, rainwater harvesting, reducing shower time, and using water-saving devices, among others. Indeed, Tijs et al. (2017) state that, to promote pro-environmental behavior, it is necessary to provide information on the environmental costs of consuming energy, water, gasoline, among others. For example, Otaki et al. (2024) found that applying discounts to low-consumption households as an incentive for water conservation led to a reduction in their use, but had no noticeable effect on high-consumption households, as low water consumers wished to keep their bills low. Previously, de Koning et al. (2016) showed that the middle-class population in Vietnam was motivated to adopt environmentally friendly activities for health reasons and, above all, to save money.

It is worth noting that few studies compare the effectiveness of monetary appeals versus environmental appeals in reducing water use (Fielding et al., 2013; Tijs et al., 2017).

## 2.4 Moral commitment in sustainable water management and intention

According to Imani et al. (2021), moral commitment is one of the variables that directly affect individuals' intention to adopt more sustainable practices. Indeed, Menatizadeh et al. (2024) demonstrated that moral commitment is a variable that reinforces farmers' intention to engage in practices that lead to the conservation of water resources. Likewise, Yayla et al. (2020) showed that employees of eco-friendly hotels exhibited a higher moral commitment to carrying out environmentally friendly activities.

However, Almulhim and Abubakar (2024) highlighted that individuals in Saudi Arabia do not perceive water conservation as a moral commitment, as they associate it with socio-economic characteristics.

# 3 Materials and Methods

## 3.1 Sample and sampling technique

The present research was conducted in the city of Puebla, Mexico, which is the fifth most populated city in the country. The sample size was calculated using the formula for an infinite population (more than 500,000 elements) (Pelayo and Arroyo, 2015), resulting in 385 elements; however, a total of 450 surveys were obtained. Accordingly, the sample consisted of citizens from this locality (Balbin-Romero et al., 2024; Zhang et al., 2025), who were invited to complete the online survey. For this purpose, a non-probabilistic convenience sampling technique was applied, as this method allows saving resources and time, while also providing original responses (Jabeen et al., 2023; Keles et al., 2023).

Prior to the implementation of the study, the instrument was subjected to a validation process through expert judgment. Five specialists, both national and international, evaluated the relevance, clarity, and coherence of the items in relation to the variables of the EGCI model (Consumption Economics, Sustainable Water Management, Moral Commitment, and Intention of Sustainable Practices) (see Figure 1). Subsequently, a pilot survey was administered to 90 individuals in order to verify the comprehension and wording of the questions, as well as their ability to adequately measure each construct. The results of the pilot test confirmed the face and content validity of the instrument, and minor wording adjustments were made to improve its precision. Finally, the administration of the final survey was carried out between January and March 2025.

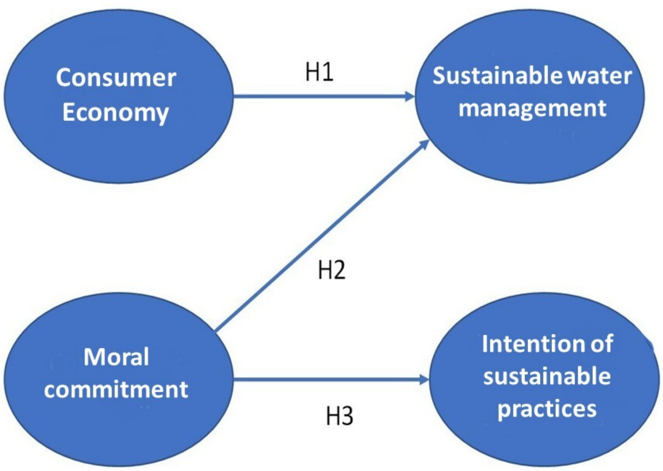


**Figure 1.** Study model based on Chenoweth et al. (2016); Lowe et al. (2015); Salem and Ertz (2023); Imani et al. (2021); Keles et al. (2023); Rusyani et al. (2021).

### 3.2 Instrument

The questionnaire administered is divided into three parts. In the first part, respondents were asked about their current habits regarding water use in their homes (Molina et al., 2018; Rivera-Pérez et al., 2020; Zulqarnain and Khan, 2024). In the second part of the questionnaire, the variables of the study model were measured using a 5-point Likert-type scale, where $1 =$ strongly disagree and $5 =$ strongly agree. In the third part, demographic data of the participants were collected.

With regard to the measurement of the consumption economics variable, the items were based on Lowe et al. (2015), Salem and Ertz (2023), and Chenoweth et al. (2016). Regarding moral commitment, the items were based on Lowe et al. (2015), Salem and Ertz (2023), and Chen (2020). For sustainable water management, the items were based on Chenoweth et al. (2016) and Molina et al. (2018). Finally, for the variable intention to adopt sustainable practices, the items were based on Lowe et al. (2015), Salem and Ertz (2023), and Chenoweth et al. (2016).

In relation to the latter, items were generated to test the following hypotheses:

**H1:** A reduction in the costs associated with household water consumption will lead to the implementation of sustainable water management practices.

**H2:** A high level of moral commitment toward environmental protection is a decisive predictor of sustainable water management in the domestic/citizen context.

**H3:** A high level of moral commitment toward environmental protection positively and significantly influences the intention to adopt sustainable water-care practices.

### 3.3 Data analysis method

For the analysis of demographic data, SPSS software version 25 was used. Regarding the analysis of the study model, the partial least squares structural equation modeling (PLS-SEM) technique was applied using SmartPLS 4. One of the advantages of using PLS-SEM is that it does not require any particular restrictions regarding data normality and is also applicable to the analysis of relatively small datasets (Hair Jr. et al., 2019). Likewise, the use of PLS-SEM allows for the prediction of the effects of independent variables on dependent variables (Thanki et al., 2022).

## 4 Results and Discussion

### 4.1 Demographic profile of respondents

Regarding the age of the respondents, 70.3 % were between 18 and 23 years old, 10.5 % were between 24 and 29, 0.8 % between 30 and 35, 2.3 % between 36 and 41, 2.3 % between 42 and 47, 4.5 % between 48 and 53, and 1.5 % were older than 53. With respect to sex, 59 % were women and 39.1 % were men. Regarding educational level, 84.2 % were undergraduate students, 5.3 % were enrolled in a master's program, 1.1 % were doctoral students, and 1.5 % were pursuing a specialization.

### 4.2 Reliability and validity analysis

Regarding the reliability and validity of the constructs in the conceptual model, these were assessed following the recommendations of Hair Jr. et al. (2019). Convergent validity was tested using factor loadings ($> 0.70$), average variance extracted (AVE $> 0.50$), Cronbach's alpha ($> 0.70$), and composite reliability. Table 1 shows that the constructs exhibit convergent validity; however, the GSA3 variable did not achieve the acceptable factor loading and was therefore removed, after which the analysis was conducted again.

Regarding discriminant validity, Henseler et al. (2015) described the Heterotrait–Monotrait (HTMT) criterion for assessing discriminant validity, with a cutoff value of 0.90; therefore, discriminant validity is indicated in Table 2, where the diagonal values correspond to the square root of the AVE. In addition, variance inflation factor (VIF) values were measured to detect multicollinearity problems, since, according to Kock (2015), the values must be below 5 for the variables used in this study to be considered free of multicollinearity issues. Table 3 shows that the established criteria are met for each construct.

**Table 1.** Reliability and validity results of the model

| Items | Factor loadings | Cronbach's alpha | Composite reliability | AVE |
|---|---|---|---|---|
| **Consumption economics** | | | | |
| ECON1 | 0.723 | 0.835 | 0.846 | 0.671 |
| ECON2 | 0.819 | | | |
| ECON3 | 0.828 | | | |
| ECON4 | 0.896 | | | |
| **Moral commitment** | | | | |
| COM_M1 | 0.934 | 0.960 | 0.963 | 0.892 |
| COM_M2 | 0.914 | | | |
| COM_M3 | 0.967 | | | |
| COM_M4 | 0.963 | | | |
| **Sustainable water management** | | | | |
| GSA1 | 0.931 | 0.854 | 0.895 | 0.773 |
| GSA2 | 0.792 | | | |
| GSA4 | 0.909 | | | |
| **Intention of sustainable practices** | | | | |
| INT1 | 0.732 | 0.823 | 0.858 | 0.650 |
| INT2 | 0.847 | | | |
| INT3 | 0.847 | | | |
| INT4 | 0.793 | | | |

**Table 2.** Heterotrait–Monotrait criterion

| | COM_M | ECON | GS | INT |
|---|---|---|---|---|
| **COM_M** | | | | |
| **ECON** | 0.823 | | | |
| **GS** | 0.826 | 0.872 | | |
| **INT** | 0.483 | 0.679 | 0.690 | |

**Table 3.** Hypothesis testing results

| Hypothesis | VIF | Path | $p$-value | $f^2$ | Result |
|---|---|---|---|---|---|
| ECON → GSA | 2.266 | 0.413 | 0.000 | 0.228 | Not rejected |
| COM_M → GSA | 2.266 | 0.461 | 0.000 | 0.283 | Not rejected |
| COM_M → INT | 1.000 | 0.447 | 0.000 | 0.250 | Not rejected |

## 4.3 Structural model evaluation

After confirming the validity of the measurement model, the explanatory power ($R^2$) and predictive relevance ($Q^2$) of the model were tested. The evaluation of the structural model was carried out by applying the PLS bootstrapping algorithm with a complete output, using a subsample of 5,000 and a one-tailed $t$-test, with a significance level of 0.05 (Hair Jr. et al., 2019), as shown in Figure 2.

Based on the results obtained, the variable that had the greatest impact on sustainable water management was moral commitment ($\beta = 0.461$, $p < 0.001$); therefore, Hypothesis 1 is not rejected. This was followed by the consumption economics variable ($\beta = 0.413$, $p < 0.001$); thus, Hypothesis 2 is not rejected. Finally, the moral commitment variable positively and directly affects the intention to adopt sustainable practices ($\beta = 0.447$, $p < 0.001$); therefore, Hypothesis 3 is not rejected.

Regarding the coefficient of determination ($R^2$), the effects of the consumption economics and moral commitment variables on sustainable water management were examined, as well as the effect of moral commitment on the intention to adopt sustainable practices. The $R^2$ obtained was 0.669, which is moderate to high for explaining the variation in sustainable water management based on the consumption economics and moral commitment variables. In turn, the $R^2$ obtained to explain the variation in the intention to adopt sustainable water-care practices was 0.200 (weak).

Finally, the Stone-Geisser predictive relevance $Q^2$, which is an indicator of out-of-sample predictive power or predictive relevance, where a value greater than 0 for a specific endogenous variable indicates the predictive relevance of the model for a dependent construct (Hair Jr. et al., 2019), showed that the sustainable management construct has a $Q^2 = 0.640$ and the intention construct has a $Q^2 = 0.183$.

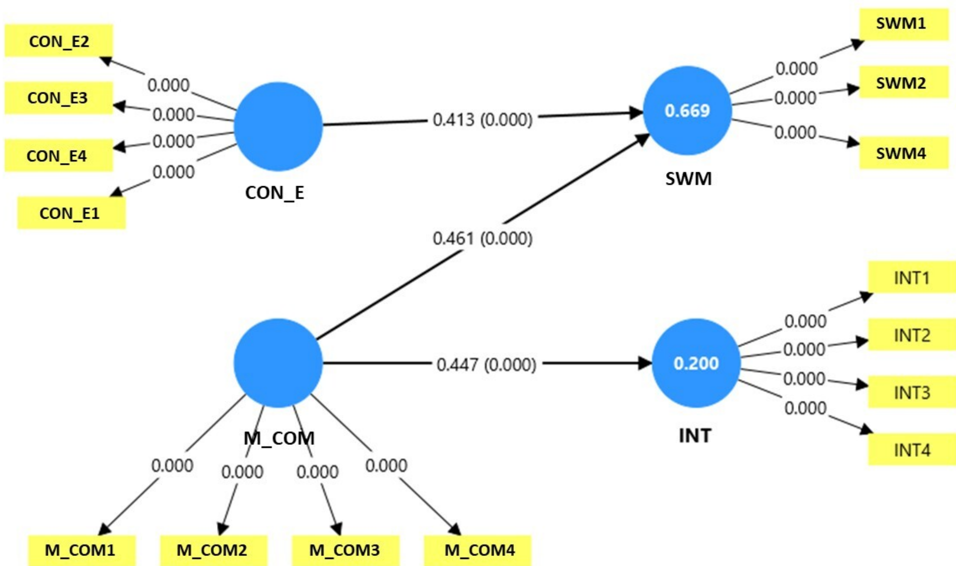


**Figure 2.** Results of the structural model evaluation.

## 5 Discussion

As observed in the results, it is necessary to provide information on the environmental costs of water consumption, as well as on the monetary costs borne by users, as mentioned by Tijs et al. (2017), raising awareness among individuals about saving water when spending time in the shower or when letting water run while washing dishes. In addition, applying discounts to low-consumption households for water conservation can help reduce both their water use and monetary expenses simultaneously (Otaki et al., 2024). For this reason, Hypothesis 1 was not rejected.

Regarding the moral commitment variable, it was the one that most strongly and positively impacted sustainable water management; therefore, Hypothesis 2 was not rejected. These results confirm the findings reported by Imani et al. (2021), who demonstrated that moral awareness is a predictive variable in environmental protection activities. Likewise, Müller-Pérez et al. (2022) pointed out that Mexican citizens are aware of environmental problems and, therefore, feel morally obliged to adopt pro-environmental behaviors.

Finally, moral commitment positively and directly affected the intention to adopt sustainable water-care practices; thus, Hypothesis 3 was not rejected. Some previous studies have shown that this variable is important to consider in environmental protection studies (Müller-Pérez et al., 2022; Yayla et al., 2020), since citizens who exhibit higher moral commitment have greater motivation to engage in environmentally friendly activities. Therefore, it is necessary to engage future generations in improving water-use efficiency, as well as to raise awareness about the conservation and sustainable use of water resources.

# 6 Conclusions

The present study focused on analyzing the factors that influence citizens' intention to adopt sustainable water-care practices, integrating the variables of the EGCI model from a responsible consumption perspective. Among the most innovative results, it is evident that moral commitment not only directly and significantly influences sustainable behavioral intention, but also has a positive impact on efficient water management, a finding that underscores the ethical dimension as a key driver of water conservation among students in Puebla.

Additionally, confirmation of the positive effect of the perceived reduction in costs associated with water consumption on sustainable management provides a concrete economic perspective that strengthens the understanding of the motivators of citizen behavior. These results highlight the need to integrate multidimensional approaches—combining moral and economic factors—into the design of policies and educational campaigns. Finally, the validated instrument represents a valuable and pioneering tool for future research related to water conservation.

## 6.1 Theoretical and practical implications

Regarding theoretical implications, this study can be used as a basis for future research focused on the conservation of water, electricity, gas, among others. In addition, it provides guidance for extending economic and responsible consumption study models within sustainability and circular economy theories. However, further studies are needed that combine economics, ecology, and public policy to address the water problem from a comprehensive perspective.

With respect to practical implications, the results highlight the need to design campaigns targeting different sectors of society to modify consumption patterns through initiatives that promote the use of water-saving devices in households, as well as to inform citizens about the different ways in which water can be reused. Similarly, it is important to encourage water supply companies to implement dynamic tariffs or subsidies to promote efficient water consumption among citizens; for example, implementing discounts for semiannual or annual advance payments and, at the same time, offering water-saving devices with monthly charges included in utility bills.

## 6.2 Future lines of research

Regarding future lines of research in water conservation, studies may be considered that evaluate how technology (IoT, artificial intelligence) can improve water-use efficiency. Likewise, studies on citizen behavior focused on strategies for water recycling and reuse in different sectors, such as the automotive industry, may be conducted. Finally, comparative studies on sustainable water behavior in other states of the Mexican Republic and in other countries are recommended.

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# Authors' contribution

**J.M.P.:** Conceptualization, Formal analysis, Data curation, Project administration, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review & editing. **A.A.D.:** Conceptualization, Formal analysis, Data curation, Project administration, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review & editing. **M.S.E.:** Conceptualization, Formal analysis, Data curation, Project administration, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review & editing. **I.Y.V.:** Conceptualization, Formal analysis, Data curation, Project administration, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review & editing. **R.A.B.:** Conceptualization, Formal analysis, Data curation, Project administration, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review & editing.

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*Special Issue* / Edición Especial
Quality of life and sustainability



# Critical points and socio-ecological dynamics of tomato (*Solanum lycopersicum* L.) cultivation in low-tech greenhouse systems in Colombia

# Puntos críticos y dinámicas socioecológicas del tomate (*Solanum lycopersicum* L.) bajo cubierta en núcleos productivos colombianos

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**Abstract**

Tomato cultivation in Colombia must balance market demands while minimizing environmental impact. Despite productivity improvements, it still depends on external inputs such as phytosanitary products, fertilizers, and infrastructure that produce waste. Hence, the transition to sustainable cropping requires recognition of positive aspects and areas for improvement. This study aims to identify critical points in tomato cultivation under low-tech greenhouses in two different geographic regions in Colombia. The socio-ecological systems framework was adopted to promote a transition to sustainable production. The methodology considered the selection of 13 variables and 33 topics of analysis collected through the application of semi-structured interviews with key actors (32) and structured interviews with tomato producers (124). Fourteen critical points were identified across social, environmental, and productive components, categorized into: system of units and resources, governance, actors and production systems, and interactions. Notable points include ecosystem services related to water and soil provision, land tenure, technology adoption, and pollutant reduction practices. These points are crucial for driving a shift towards sustainable production in the regions studied.

***Keywords***: Sustainability, greenhouses, pesticides, residues, food safety, sustainable practices.

**Resumen**

La producción de tomate en Colombia enfrenta el reto de equilibrar las demandas de mercado y disminuir el impacto sobre los ecosistemas. Aunque la productividad del cultivo ha aumentado, la dependencia de insumos externos como productos fitosanitarios, fertilizantes e infraestructura que generan residuos sigue siendo alta, por lo que transitar hacia un sistema productivo sostenible requiere el reconocimiento de los aspectos positivos y de mejora. Por lo anterior, el objetivo de este estudio es identificar puntos críticos del cultivo de tomate bajo cubierta en dos regiones geográficas diferentes de Colombia. Para esto, se usó el enfoque del marco de sistemas socioecológicos para facilitar la transición hacia sistemas productivos sostenibles. La metodología contempló la selección de 13 variables y 33 tópicos de análisis que fueron recogidos a través de la aplicación de entrevistas semiestructuradas a actores clave (32) y estructuradas a productores (124), identificándose 14 puntos críticos de los componentes sociales, ambientales y productivos, categorizados en: sistema de unidades y recursos, gobernanza, actores y sistemas productivos, e interacciones. Se destacaron los servicios ecosistémicos de provisión de agua y suelo, la tenencia de la tierra, la adopción de tecnologías y las prácticas de reducción de contaminantes. Estos puntos son clave para impulsar un cambio hacia una producción sostenible en las regiones estudiadas.

***Palabras clave***: Sostenibilidad, invernaderos, plaguicidas, residuos, inocuidad, prácticas sustentables.

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# 1 Introduction

Food production is a constant challenge worldwide (Pérez-Vázquez et al., 2018). In Latin America, agricultural production is caught between the need to achieve the volumes and quality demanded by markets and the need to reduce impacts on ecosystems (Benton et al., 2021). Nevertheless, crop selection is largely determined by smallholder-based logic (Berdegué and Escobar, 2004), in which profitability tends to prevail over environmental considerations and over the health of both producers and consumers. This dynamic has contributed to the emergence of a market that places greater value on organoleptic characteristics than on product safety.

A clear example of this situation is tomato (*Solanum lycopersicum* L.), which ranks first worldwide in terms of production volume and second in cultivated area. China is the leading producer, with 67,636,724.8 t in 2021. In Latin America and the Caribbean, Colombia ranks fifth with a production of 875,436.86 t, after Mexico, Brazil, Argentina, and Chile (FAOSTAT, 2023).

In Colombia, tomato cultivation is carried out both in open-field conditions and under protected environments. Over the past two decades, both the cultivated area and production under protected systems have shown a steady increase, rising from 11 % in 2009 to 41.45 % in 2019. In 2022, 10,079 ha were planted under open-field conditions, with an average yield of 27 t/ha, while 7,616 ha were cultivated under protected systems, achieving an average yield of 83.74 t/ha (Agronet, 2024). The yield gap between these production systems is largely attributed to the effect of protective structures, which enhance the productive potential of the plant material (J. Jaramillo et al., 2012).

In 2022, Boyacá led protected tomato production in Colombia, with a total of 209,316 t. Although it remains among the three most productive regions, yields have stagnated in contrast to the rapid expansion of the cultivated area, which increased by 590 % over a seven-year period, reaching 2.185 ha (Agronet, 2024). Cundinamarca, ranking second, reported 869 ha under cultivation in 2022. Despite the continued expansion of cultivated areas in both regions, yields have exhibited a declining trend (Agronet, 2024).

In the ongoing global transition toward sustainable production systems (Food and Agricultural Organization, 2021), coordinated efforts among producers, technical specialists, and researchers from diverse fields of knowledge are essential. Productive systems must be understood as livelihoods embedded within the environmental, socioeconomic, and cultural dynamics of a given territory. Within this context, the objective of this study is to analyze protected tomato production systems by identifying critical points that may affect the sustainability of the production process in two of Colombia's main tomato-producing regions, using a socio-ecological systems framework. This integrative analytical approach enables the formulation of multidimensional recommendations to support sustainable production.

# 2 Materials and methods

## 2.1 Description of the study area

The study considers two regions or dynamic centres of growing greenhouse tomato production: the eastern province of Cundinamarca, in the municipalities of Cáqueza, Choachí and Fómeque; and the province of Alto Ricaurte in Boyacá, in the municipalities of Sutamarchán, Santa Sofía, Sáchica, Tinjacá and Villa de Leyva (Figure 1).

Currently, the municipalities studied produce approximately 27 % of the tomatoes harvested under protected conditions in Colombia, with 150,669 tonnes produced in the municipalities of Boyacá and 12,207 tonnes produced in the municipalities of Cundinamarca (Agronet, 2023).

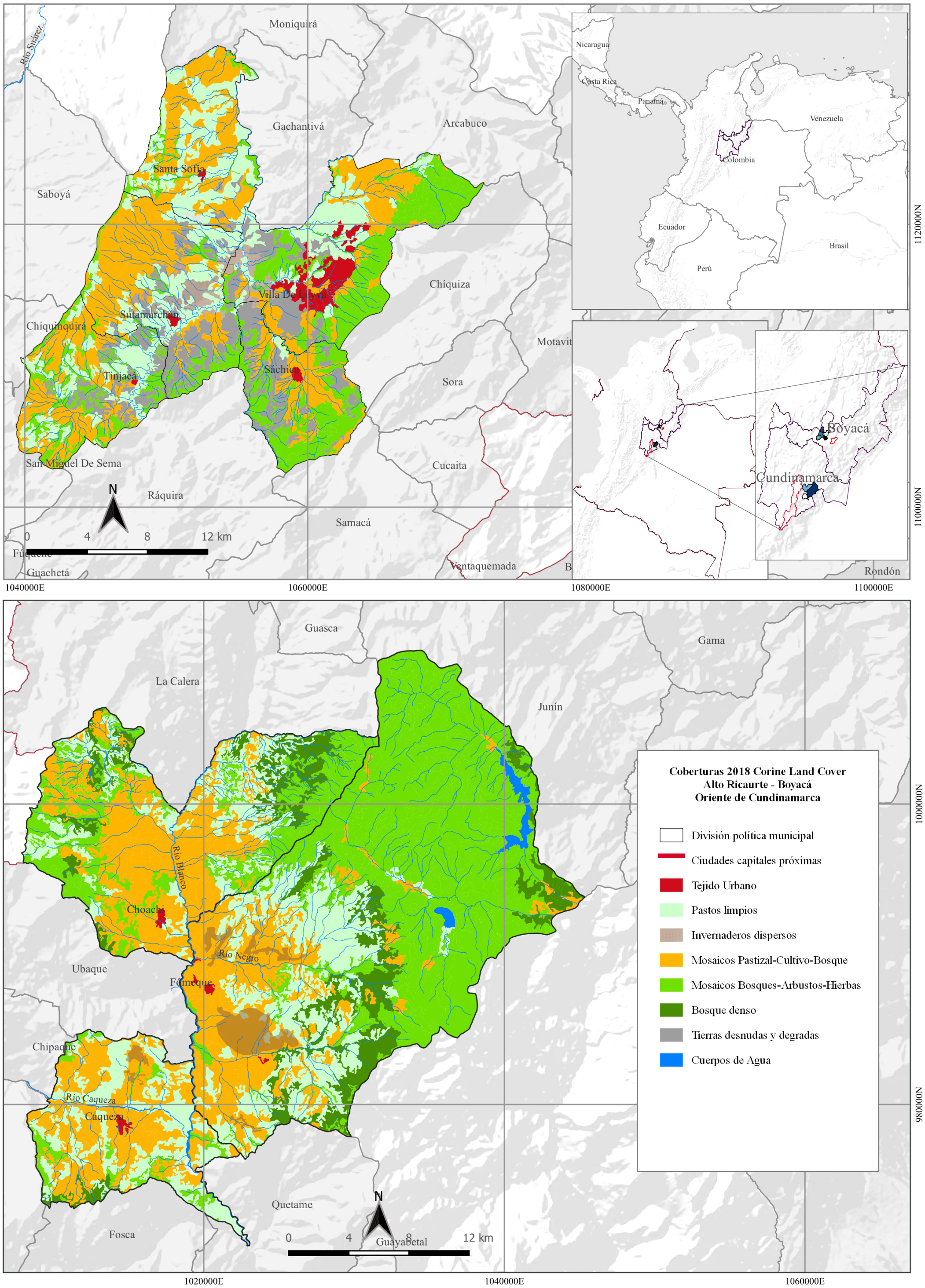


**Figure 1.** Location of the study area. Source: The authors, based on Corine Land Cover.

## 2.2 Components and variables to address the analysis of socio-ecological system

The analysis of socio-ecological systems (SES) integrates environmental and socioeconomic dimensions, allowing for a territorial understanding in which social and biophysical agents interact and provide feedback across multiple temporal and spatial scales (Ostrom, 2009).

Several theoretical approaches have been proposed to address socio-ecological analysis; however, the framework developed by McGinnis and Ostrom (2014) stands out for its clear, coherent, flexible, and context-adaptable organizational structure (Nagel and Partelow, 2022). These strengths help overcome limitations such as the complexity involved in interpreting results and the difficulty of incorporating a dynamic perspective into the variables analyzed (Hinkel et al., 2015).

In Colombia, this framework has been used primarily to address water resource management (Díaz-Pinzón et al., 2024; Gomez-Jaramillo et al., 2024), and more limitedly to analyze agroforestry food systems (Rodríguez et al., 2023) and cocoa production systems (Quiroga et al., 2024). In this sense, the present study represents an effort to advance the integration of sustainable production with socio-ecological systems analysis.

The framework disaggregates socio-ecological systems into five main components:

- **Resource system and resource units:** it describes the natural resources available within the territory.
- **Governance system:** it examines decision-making processes, including rules, norms, and land tenure arrangements.
- **Actors and production system:** it characterizes the population and productive actors within the region.
- **Interactions:** it describes the relationships among components, including existing problems and conflicts within the territory.
- **Exogenous conditions:** it addresses broader social, economic, political, and ecosystem characteristics. This component was addressed in a complementary manner through a review of secondary information.

Using the expert consultation method (Herrera-Masó et al., 2022), which is comparable to the Delphi method in terms of expert panel composition (López-Gómez, 2018), workshops and meetings were conducted in a hybrid format (virtual and in-person). The expert panel included researchers with experience in environmental, social, economic, and productive topics, with particular emphasis on soils, pests, diseases, and post-harvest processes. Through successive rounds of consensus-building, a set of variables was defined for analysis within each component. As a result, a matrix comprising 13 variables and 33 topics was consolidated (Table 1).

Based on secondary information, exogenous conditions were addressed by considering demographic trends, marginalization and poverty indices, and sustainable production policies with relevance at the territorial level.

## 2.3 Data Collection and Analysis

The study included the design and application of semi-structured interviews with key actors (Conagua, 2013) and structured interviews with tomato producers. These instruments were applied between December 2022 and February 2023.

The selection of key actors was based on a review of secondary information and consultations with local government offices, recognizing experience in sustainable production. Accordingly, actors involved in environmental, social, and productive processes within the region were considered. In the case of producers, fieldwork focused on rural communities historically recognized for tomato production, and farmers to be interviewed were identified in collaboration with local leaders from each region.

**Table 1.** Synthesis of variables included in the socio-ecological matrix.

| Component | Variable | Topic |
|---|---|---|
| Resource System and Resource Units | Ecosystem services | SUR1. Key actors who, when consulted about ecosystem services, place greater emphasis on productive activities.<br>SUR2. Ecosystem services most frequently highlighted by key actors.<br>SUR3. Ecosystem services most commonly recognized by producers. |
| | Water resources | SUR4. Key actors who perceive water resources as scarce and water quality as moderate.<br>SUR5. Producers who perceive that water availability during the dry season is sufficient for households and crops. |
| | Conservation areas | SUR6. Key actors who identify local, regional, and national conservation areas.<br>SUR7. Producers who consider the protection of natural resources to be as important as agricultural production.<br>SUR8. Producers who report having conservation areas within their farms. |
| Governance | Land size | G1. Perceptions of key actors regarding land size (productive unit) per family.<br>G2. Average land area cultivated by producer households. |
| | Land tenure | G3. Perceptions of key actors regarding land tenure type.<br>G4. Percentage of producers who identify themselves as landowners. |
| | Local organization | G5. Key actors who identify the presence of local organizations.<br>G6. Producers affiliated with a local organization. |
| Actors and Production System | Main economic activities | A1. Main economic activities identified by key actors.<br>A2. Key actors who perceive tomato cultivation as an important activity in the region. |
| | Characteristics of tomato producers | A3. Average area cultivated by households for tomato production.<br>A4. Average age of producers.<br>A5. Educational level of producers.<br>A6. Household size of producers. |
| | Relevant characteristics of tomato cultivation | A7. Producers by type and origin of plant material.<br>A8. Producers by type of practices associated with soil health (disinfection and fertilization).<br>A9. Producers affected by major phytosanitary problems.<br>A10. Producers by type of irrigation system and water source.<br>A11. Production level and percentage of producers by type of marketing and certification. |
| | Main production constraints | A12. Main production constraints perceived by key actors. |
| Interactions | Environmental issues | I1. Main environmental problems described by key actors.<br>I2. Producers who perceive that tomato cultivation negatively impacts the environment.<br>I3. Main negative environmental impacts recognized by producers. |
| | Social issues | I4. Main social problems described by key actors. |
| | Sustainability-oriented practices | I5. Producers who implement at least one sustainability-oriented practice.<br>I6. Main sustainability-oriented practices used by producers. |

The designed instruments underwent expert review and were evaluated by professionals providing technical assistance for tomato cultivation in the two study regions. In addition, the structured interview format was validated with four producers (two per region). Finally, both structured and semi-structured interviews were administered in person by researchers involved in the design of the instruments, who were familiar with their objectives and capable of clarifying and expanding upon questions when necessary. This approach ensured higher response rates and the collection of reliable information for both open- and closed-ended questions.

The semi-structured interview format consisted of 16 questions, and a total of 32 interviews were conducted with key actors (16 per region), including representatives from regional government (1), local government (18), independent technical advisors (3), nursery operators (1), a project technical leader (1), producers with experience in sustainable practices (7), and a bio-input producer (1). All interviews were audio-recorded, transcribed, and consolidated for subsequent analysis.

The structured interview format included 39 questions organized into five sections. A total of 124 interviews (62 per region) were conducted using non-probabilistic convenience sampling. Data were collected in hard copy, systematized, and analyzed using descriptive statistics in Excel and multiple correspondence analysis (Johnson and Wichern, 2002).

## 3 Results and Discussion

At the local level, most municipalities within the study area are classified as sixth-category municipalities. This classification is based on their low population density, which does not exceed 10,000 inhabitants, and their current revenues of unrestricted allocation, which are annually below 15,000 current legal monthly minimum wages (approximately USD 5,517,441). This situation results in smaller governmental organizational structures.

At the regional scale, the study area is located within the departments of Cundinamarca and Boyacá, which are strategically connected to the national capital. According to the 2023 Departmental Competitiveness Index, these departments rank 9th and 10th, respectively, out of a total of 32 (Consejo Privado de Competitividad and SCORE-Universidad del Rosario, 2023). Both departments stand out for their progress in infrastructure, information and communication technology (ICT) adoption, education, and innovation. However, each department faces specific challenges. Boyacá must improve aspects related to the business environment, labor market, market size, and the sophistication and diversification of its economy. In contrast, Cundinamarca faces significant challenges related to environmental sustainability, public health, and the financial system.

In terms of public policy, Colombia has a robust regulatory framework that promotes sustainable agriculture, including the General Law on Agricultural and Fisheries Development (Congreso de Colombia, 1993), the National Policy on Sustainable Production and Consumption (MAVDT, 2010), and the National Circular Economy Strategy (MADS and MCIT, 2019). These instruments have guided the formulation of national and departmental government plans aimed at fostering sustainable agricultural systems. Nevertheless, Pérez (2020) emphasizes the need to strengthen coordination between the environmental and agricultural sectors to implement measures that effectively balance conservation and production, as well as to increase efforts to raise consumer awareness regarding the quality, safety, and environmental impacts of the food products they consume.

Further analysis of the remaining components identified 14 critical points, organized within the components of resource systems and resource units, governance, actors and production systems, and interactions (Figure 2).

Before analyzing the identified critical points by component, it is important to highlight that some of these points constitute feedback loops within the system, which explain the complex nature and the associated behavioral patterns of the socio-ecological system (Preiser et al., 2018). In this way, feedback loops contribute to the understanding of vicious cycles of barriers that perpetuate and hinder system performance (Hanf et al., 2025). Defining and understanding these loops supports decision-making processes (Rodriguez-Gonzalez et al., 2020), in this case aimed at advancing toward sustainable production. The feedback loops identified in the socio-ecological systems analyzed in this study are primarily related to components of actors and governance, particularly land tenure, local organization, and technological lag.

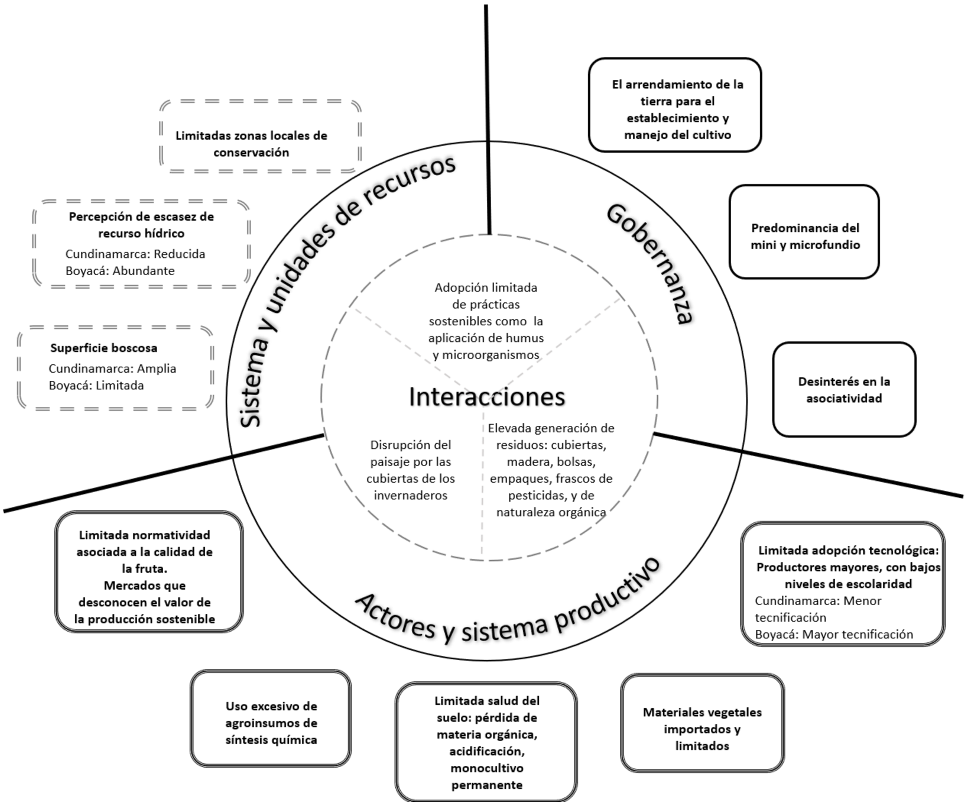


**Figure 2.** Synthesis of the identified critical points. Source: the authors.

## 3.1 Multiple Correspondence Analysis

Based on the multiple correspondence analysis, the first two dimensions explain 25.21 % of the variability of the observed data, a proportion considered adequate (Asan and Greenacre, 2008) and allow for the differentiation of three groups of producers (Figure 3).

Group 1. Sustainability-oriented producers: landowners who report no water scarcity and recognize benefits from nature such as the provision of clean air. They are aware of the negative impact of agrochemicals on human health; therefore, they incorporate sustainability-oriented practices such as the use of biofertilizers, biopesticides, and practices to protect the soil.

Group 2. Traditional agriculture producers: they rent the land and, therefore, do not own farms or conservation areas; they perceive water scarcity during the dry season and report not conducting soil analyses to support decision-making in crop management. These producers state that they are unaware of the negative effects of agrochemical use and report not using sustainability-oriented practices in their crops.

Group 3. Producers with environmental awareness and conventional management: with other forms of land tenure (they possess the land without a formal title or in partnership with other producers), they report having farms or conservation areas and perceive that water is sometimes sufficient during the dry season. They recognize ecosystem services such as water provision and the provision of food and firewood. They acknowledge that agrochemical use affects both the environment and people. Although these producers report not implementing sustainability-oriented practices, they declare conducting soil analyses in their crops for fertilization purposes.

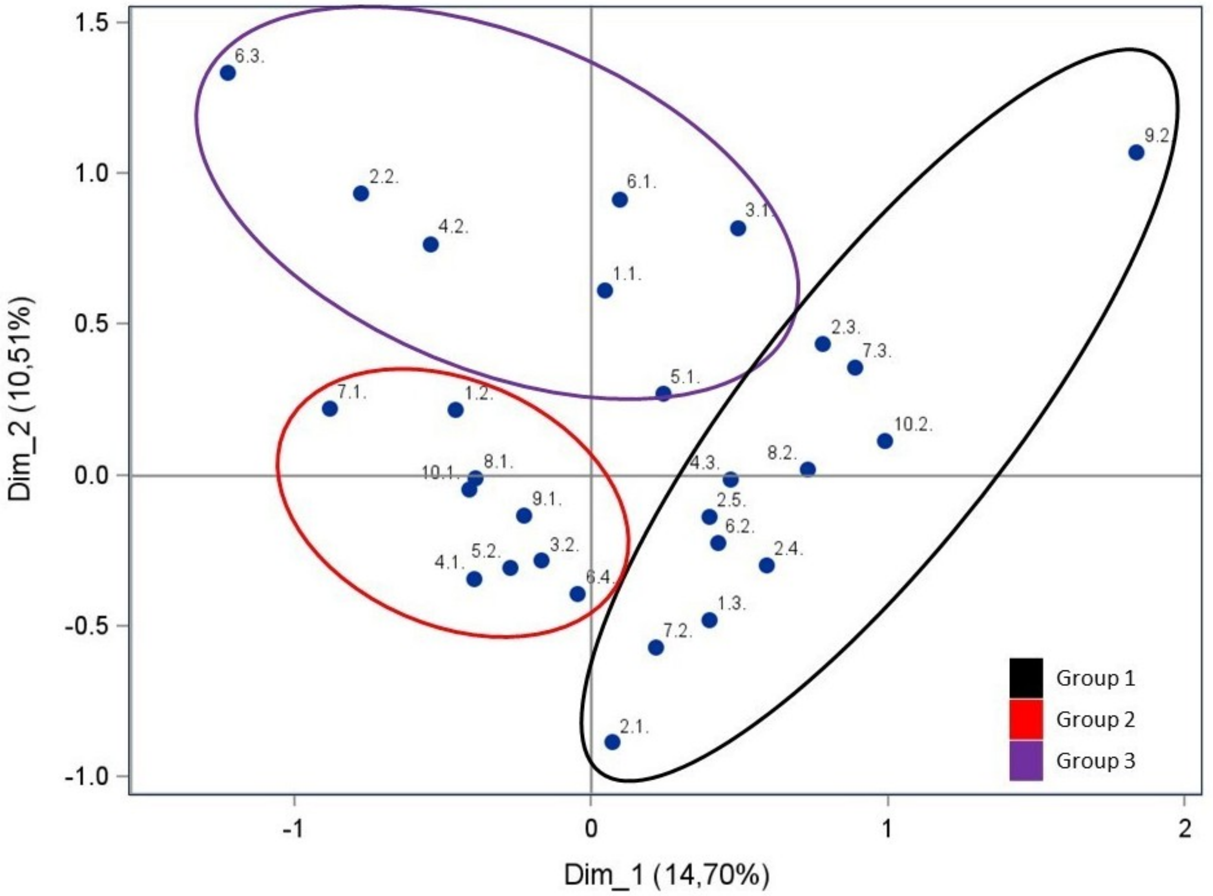


**Figure 3.** Multiple correspondence analysis.

Component System and resource units: 1. Water availability in summer (categories 1.1. Sometimes, 1.2. Insufficient, 1.3. Sufficient), 2. Benefits of nature (2.1. Water for domestic use and crops, 2.2. Water for domestic use and crops; food and firewood from the forest, 2.3. Water for domestic use and crops; clean air and other benefits, 2.4. Clean air, other benefits, 2.5. Other benefits), 3. Conservation areas or plots (3.1. Yes, 3.2. No). Governance: 4. Tenure (4.1. Tenant, 4.2. Other tenure, 4.3. Owner). Actors and production system: 5. Soil analysis (5.1. Yes, 5.2. No), 6. Perceived impact of agrochemicals (6.1. Yes, on the environment, 6.2. Yes, on people, 6.3. Yes, on people and the environment, 6.4. No). Interactions: 7. Applies biofertilizers (7.1. No, 7.2. Yes, one, 7.3. Yes, two or more), 8. Implements soil protection practices (8.1. No, 8.2. Yes, one or two), 9. Practices for biodiversity protection (9.1. No, 9.2. Yes, one or two), 10. Applies biopesticides (10.1. No, 10.2. Yes, one or more).

## 3.2 Resource system and resource units

Three critical points: forest cover, perception of water resource scarcity, and local and regional conservation areas.

Perceptions regarding water resource availability were contrasting between the two regions, as was the recognition of national conservation areas. In Boyacá, greater water scarcity is perceived, and conservation areas are more limitedly recognized, compared to Cundinamarca (Table 2).

**Table 2.** Results for variables of the resource system and resource units.

| Variable | Topic | Boyacá | Cundinamarca |
|---|---|---|---|
| Ecosystem services | SUR1 | 56.2 % | 12.5 % |
| | SUR2 | – Water resource availability<br>– Soils suitable for agriculture | – Water resource availability |
| | SUR3 | – Water for domestic use (87 %)<br>– Food–firewood (65 %)<br>– Clean air (50 %) | – Water for domestic use (71 %) |
| Water resources | SUR4 | 93.8 % | 25 % |
| | SUR5 | 26 % | 61 % |
| Conservation areas | SUR6 | Local or regional (37.5 %)<br>National (6.2 %) | Local or regional (56.2 %)<br>National (37.5 %) |
| | SUR7 | 98 % | 97 % |
| | SUR8 | 35 % | 48 % |

In Boyacá, a low extent of stable and conserved forest area was observed, affecting strategic ecosystems. Ramos et al. (2022) reported that remaining forest patches are disappearing due to agricultural expansion. In the municipalities studied, stable forest area does not exceed 150 ha (Departamento Nacional de Planeación, 2023), representing less than 2 % of the total area.

Water scarcity has affected economic activities, highlighting the need to balance conservation and production actions. It is essential to identify conservation areas and develop restoration and land-use conversion strategies to recover forest cover.

In contrast, in Cundinamarca, municipalities contain between 3,000 and 6,000 ha of stable forest (Departamento Nacional de Planeación, 2023), representing approximately 13 % of their total area. This ensures good access to water resources and a perception of water abundance. Nevertheless, the landscape has been transformed into a mosaic of forest fragments, pastures, páramo areas, and croplands, with a trend toward decreasing conservation areas and increasing community vulnerability (Buitrago, 2022).

Multiple correspondence analysis revealed that the group implementing sustainable practices perceives lower water scarcity and recognizes additional ecosystem services, such as clean air.

The analysis of the resource system and resource units made it possible to understand both the status of natural resources essential for crop development and the relationship between producers and nature. In Boyacá, a greater impact of agricultural activity and increasingly scarce natural resources are perceived, which is related to the geographical location and productive history of each region. In this regard, the forms of interaction and use of natural resources in each region have caused different disruptions to the landscape matrix. This is particularly evident in Boyacá, where the rural landscape has been modified by greenhouse structures, reducing its visual appeal and negatively affecting tourism in internationally recognized areas such as the Villa de Leyva Valley. This situation, along with the perception of water scarcity, underscores the need to transition toward sustainable production systems. In contrast, Cundinamarca, due to greater water availability and the resulting higher forest cover, does not exhibit such a pronounced impact on the landscape.

## 3.3 Governance

Three critical points: predominance of private property and smallholdings in both regions; as well as limited participation in local organizations (Table 3).

**Table 3.** Variable governance outcomes.

| **Variable** | **Topic** | **Boyacá** | **Cundinamarca** |
|---|---|---|---|
| Land size | G1 | 1–5 ha | |
| | G2 | 2.6 ha | 1.6 ha |
| Land tenure | G3 | Landowners (with possession certificates or documents accrediting inheritance) | |
| | G4 | 41 % | 55 % |
| Local organization | G5 | 56.2 % | 68.8 % |
| | G6 | 11.3 % | 5 % |

One aspect that increases the vulnerability of tomato-producing communities and threatens system stability is the low organizational capacity of producers. Individual interests hinder collective action, which, according to Escobedo (2018), also affects other value chains such as coffee. This highlights the need for cooperation, commitment, and information flow under a win–win perspective; otherwise, the system fails due to insufficient empirical knowledge and a lack of organization (Vargas-Hernández, 2013).

Protected tomato production is intensive and small-scale, which has implications for sustainability. Gamboa et al. (2020) report an inverse relationship between sustainability and farm size. The small size of production units limits the conservation of vegetation, as productive land use is prioritized. In addition, multiple correspondence analysis shows that landowners implement more sustainable practices than tenants.

This finding is particularly relevant in Colombia, which has a land ownership Gini coefficient of 0.897 (Alzate, 2020), the third highest in Latin America, where land is concentrated in the hands of few owners while many producers are tenants. The latter do not perceive the consequences of land use beyond economic interest, underscoring the need to strengthen their environmental awareness.

The analysis of the governance component revealed strong similarities between the two study regions in terms of land tenure under private ownership, the predominance of smallholdings, and limited organizational capacity. These aspects should inform the design of sustainable production proposals for the region and are also linked to the fact that these two regions together concentrate 25 % of the country's population.

## 3.4 Actors and Production System

Five critical points were identified: low adoption of technologies, reliance on imported plant material, limited soil health, excessive use of agro-inputs, and regulatory and market lag with an emphasis on food safety (Table 4).

Interviewees in Boyacá and Cundinamarca identified horticulture and livestock production as the main economic activities, highlighting the relevance of tomato cultivation. In Boyacá, producers have an average age of 49 years; 37.1 % completed primary education, while 19.4 % did not complete it; and an average of 0.89 ha of their production unit is dedicated to tomato cultivation. In Cundinamarca, the average age of producers is 47 years; 47.5 % completed primary education and 23 % did not complete it; and 1.4 ha are dedicated to tomato production. Households in both regions consist of 3 to 4 members (Table 4).

Among the main problems associated with tomato cultivation in Boyacá, high infrastructure costs (greenhouse structures and irrigation systems) and agro-inputs stand out (56.2 %), followed by the impact of pests and diseases (37.5 %) and difficulties related to marketing and market access (37.5 %). In Cundinamarca, the most prominent issues are the impact of pests and diseases (43.8 %) and inadequate soil and water management (43.8 %).

**Table 4.** Results for the variable: Characteristics of tomato cultivation.

| Topic | Subtopic | Boyacá | Cundinamarca |
|---|---|---|---|
| A7 | Chonto type[1] | 90 % | 95 % |
| | Long-life type[2] | 10 % | 5 % |
| | It comes from a nursery | 92 % | 88.8 % |
| A8 | Fertilization based on soil analysis | 56.9 % | 56.4 % |
| | Soil disinfection using chemical products | 83.9 % | 67.7 % |
| | Application of organic matter to the soil | 16.1 % | 50 % |
| | Applies chemical fertilizers | 100 % | 100 % |
| A9 | Most frequently reported phytosanitary problems | – Tomato leafminer (*Tuta absoluta*) (53 %)<br>– Whitefly (*Trialeurodes vaporariorum*) (52 %)<br>– Gray mold (*Botrytis cinerea*) (31 %) | – Fusarium (*Fusarium oxysporum* f. sp. *lycopersici*) (32 %)<br>– Gall midge (*Prodiplosis longifila*) (23 %)<br>– Tomato leafminer (*Tuta absoluta*) (21 %) |
| A10 | Drip irrigation | 100 % | 95.1 % |
| | Main water source for irrigation | Reservoirs: 60.8 %<br>Springs and streams: 39.2 % | Reservoirs: 35.4 %<br>Springs and streams: 64.6 % |
| A11 | Average production (t/ha/year) | 51 | 32 |
| | Certification in Good Agricultural Practices | 1.6 % | 0 % |
| | Sales agreement with the buyer[3] | 72.6 % | 83.7 % |

[1] Type of tomato used for stew preparation.
[2] Type of tomato used for salad preparation.
[3] Formal and informal agreements between the producer and the intermediary for crop sales.

Of the five critical points identified, the first is related to the limited adoption of technology. Producers face difficulties in accessing reliable information and training on technologies for protected agriculture. In addition, adherence to traditional production models generates resistance to change, limiting improvements and maintaining dependence on obsolete technologies.

Cachipuendo et al. (2025), in the Ecuadorian context, note that low levels of agricultural technification restrict the appropriate use of water. This limitation is associated with low-efficiency infrastructure, poor maintenance, and the absence of measurement instruments that allow for rational control of water resources. The authors emphasize that the lack of technological innovation, together with traditional community-based irrigation management, reduces adaptive capacity to climate variability and compromises long-term crop sustainability.

Socioeconomic characteristics such as age and educational level influence crop productivity. Cano et al. (2016) indicate that higher levels of education are associated with greater productivity, whereas increasing age tends to reduce it, possibly due to limited adoption of technological innovations offered by associations, producer organizations, and scientific institutions. In Colombia, various institutions provide socially relevant knowledge; however, efforts and approaches are often duplicated, resulting in fragmented and sometimes divergent perspectives.

In terms of age structure, neither integration nor generational renewal is observed. In Colombia, as in other Latin American countries, family farming is dominated by an aging male labor force (70 %). This is largely due to youth migration to urban areas driven by a lack of opportunities in rural zones, which negatively affects regional economies by reducing labor availability and lowering the productivity of traditional crops (López et al., 2018), thereby placing the sustainability of tomato cultivation within the family age structure at risk.

This technological lag is also reflected in crop yields. Average production reaches 51 t/ha/year in Boyacá and 32 t/ha/year in Cundinamarca. With a national average yield of 46.6 t/ha/year, Colombia ranks 59th globally, compared to yields exceeding 300 t/ha/year in countries such as the Netherlands, Belgium, Sweden, Finland, Denmark, Ireland, and the United Kingdom (FAOSTAT, 2023). This indicates the existence of a technological gap in Colombia but also represents an opportunity to develop or adapt technologies that enhance national production.

The second critical point of this component is related to the fact that, although Colombia is the center of origin of tomato (Délices et al., 2019), the cultivars currently grown have been improved in the United States and Europe, whose breeding companies supply the seeds used in the country. However, the demand for materials more resistant to phytosanitary problems such as *Fusarium* has led to the adoption of techniques such as grafting in nurseries, combining tolerant rootstocks with high-yield hybrids such as Libertador and Roble. This practice has increased the cost of seedlings for tomato producers. Furthermore, the high demand for fresh tomato limits varietal diversity, constraining sustainable production strategies in local markets with specific uses (Ríos et al., 2014).

The third critical point highlights challenges associated with soil health:

- **Loss of organic matter:** The lack of practices that promote its retention and increase, such as the use of cover crops, limits improvements in organic matter content. Promoting such practices would reduce erosion risk and enhance microbial activity. However, they are not commonly implemented, as producers often relocate production sites when soil degradation negatively affects yields (Cuellas et al., 2019).
- **Soil acidification:** This phenomenon affects nutrient availability, thereby impacting crop quality and yield. The controlled application of liming amendments can counteract acidification and restore optimal pH levels (Dikinya and Mufwanzala, 2010).
- **Lack of crop rotation:** Continuous monocropping of tomato depletes specific nutrients and increases vulnerability to phytopathogens and insect pests. Implementing rotation plans with complementary species can restore soil biodiversity and reduce pressure on particular nutrients (Díaz et al., 2004).

The fourth critical point concerns the use of agro-inputs, which accounts for 64 % of direct production costs. Dependence on chemically synthesized products for pest and disease control reflects a constant need for external inputs to maintain crop health and productivity. Frequent pesticide use generates environmental and socioeconomic impacts (Valentín et al., 2021), while ecological imbalance favors pests that displace beneficial organisms, forcing more intensive management practices that compromise fruit safety (Caro and Cortés, 2020).

A sustainable vision of tomato production should adopt integrated pest and disease management with a preventive approach, using organomineral inputs, biological control, traps, and allelopathic strategies to reduce dependence on chemical inputs. Residue studies have reported high application levels of insecticides such as chlorpyrifos, with concentrations exceeding the maximum residue limits (MRLs) established by the European Union ($> 0.1$ ppm) (Guerrero, 2003).

Patiño et al. (2020) identified pesticide residues such as diflubenzuron and methamidophos at concentrations above established MRLs. This finding is consistent with the perceptions of interviewees, who reported high pressure from pests such as whitefly (*Trialeurodes vaporariorum*), gall midge (*Prodiplosis longifila*), and tomato leafminer (*Tuta absoluta*), whose management relies primarily on periodic applications of chemical insecticides.

These elements lead to the fifth critical point of this component: limited progress in the development and implementation of regulations associated with fruit quality. In 2014, Colombia promoted the "National Phytosanitary and Food Safety Policy" to implement a "National Pesticide Residue Plan"; however, it was not until 2022 that the Colombian Agricultural Institute (ICA) initiated national residue monitoring, and the results have yet to be published (Instituto Colombiano Agropecuario, 2022).

Advancing toward sustainable production is closely linked to regulation, pricing, and markets (Codron et al., 2014; Rodríguez-Robayo et al., 2022). Regulatory frameworks are still under development, and the main market is the Bogotá Central Wholesale Market, where certifications are not required, food safety is not inspected, and the environmental impact of production processes is not considered. This explains why only one of the 124 interviewed producers holds certification in Good Agricultural Practices, highlighting the need for markets that value sustainable production.

The analysis of the actors and production system component revealed significant similarities between the two study regions. Although Boyacá exhibits slightly greater technological innovation than Cundinamarca, a clear technological lag persists in both regions. Other topics in both Boyacá and Cundinamarca highlight the urgent need to address soil health, promote crop monitoring, and implement practices that avoid calendar-based agrochemical applications. Likewise, the importance of reflecting on tomato food safety issues in both regions was evident, particularly in terms of creating incentives for production under non-conventional and more sustainable production schemes.

## 3.5 Interactions

Three critical points were identified: greenhouse infrastructure and its management, which generate significant waste and impact the landscape, as well as progress in the adoption of sustainability-oriented practices (Table 5).

Innovations in protected agriculture, tradition and a lack of investment limit the adoption of technological improvements that could enhance efficiency and productivity. Moreover, the tomato marketing model does not provide sufficient returns to justify technological investment within the production system.

There is a marked disparity in the level of technification between the Boyacá and Cundinamarca clusters. Farmers in Cundinamarca rely more heavily on traditional and less-technified methods based on empirical knowledge. This situation is largely due to limited access to advanced technologies and insufficient training in greenhouse practices. In contrast, Boyacá has exhibited a higher level of technification, particularly in fertigation systems (Villagran and Bojacá, 2021).

This difference may be explained by better infrastructure and easier access to farms and greenhouses in Boyacá. In Cundinamarca, however, road conditions hinder access to production units, a problem exacerbated by the region's topography and climate (Villagran and Bojacá, 2021).

In both clusters, greenhouse covers adapted from the floriculture sector have been used since the 1970s. Although these structures have increased tomato production, challenges remain in optimizing crop development (Villagran et al., 2021). One of the main challenges is the implementation of structures better adapted to local climatic conditions, with greater microclimatic control and improved alignment with the ecophysiological demands of the crop, which would enhance resource-use efficiency (Rocha et al., 2021).
However, greenhouse use generates waste at the end of the materials' life cycle. The main environmental issue associated with greenhouse tomato production is the generation of solid waste, including plastic covers, wood, bags, packaging, pesticide containers, as well as organic residues.

Tomato losses during production, transport, storage, and consumption generate significant waste. According to Martínez and Quintero (2017), postharvest vegetable losses in Colombia reach 7 %. Of the 162,876 t of tomatoes produced in 2022 in the municipalities of Boyacá and Cundinamarca (Agronet, 2023), an estimated 11,401 t were lost.

Furthermore, the ecosystem service related to landscape aesthetics was not widely recognized. Greenhouse tomato cultivation alters the landscape and disrupts the ecological matrix. This effect is particularly evident in Boyacá, especially in Villa de Leyva, a globally recognized tourist area known for its desert landscapes, páramo ecosystems, lagoons, and valleys (Ramos et al., 2022). Greenhouse structures have modified the landscape, affecting tourism, which has pointed to the high visibility of greenhouses and their visual impact (Figure 4).

**Table 5.** Results for interaction variables.

| Variable | Topic | Boyacá | Cundinamarca |
|---|---|---|---|
| Environmental issues | I1 | – General impact of agricultural activities (50 %)<br>– High use of agrochemicals (37.5 %)<br>– Contamination of water sources (37.5 %)<br>– Increase in greenhouse structures and poor waste management (31.2 %) | – General impact of agricultural activities (50 %)<br>– High use of agrochemicals (37.5 %) |
| | I2 | 71 % | 21 % |
| | I3 | – High plastic use (30.6 %)<br>– Landslides and soil erosion (21 %)<br>– High use of agrochemicals (19.4 %) | – High use of agrochemicals (14.5 %)<br>– Landslides and soil erosion (9.7 %) |
| Social issues | I4 | – Youth migration and labor shortages (56.2 %)<br>– Arrival of foreign migrants (31.2 %)<br>– Insecurity, theft, and extortion (31.2 %) | – Youth migration and labor shortages (37.5 %) |
| Practices oriented towards sustainability | I5 | 79 % | 90 % |
| | I6 | – Incorporation of liquid humus into the soil (32.3 %)<br>– Crop rotation (52.2 %)<br>– Garlic–chili preparation as a biopesticide (31.3 %) | – Incorporation of liquid humus into the soil (77.4 %)<br>– Commercial microorganisms (24.2 %)<br>– Crop rotation (89.3 %)<br>– Garlic–chili preparation as a biopesticide (41.4 %) |

This impact is less pronounced in Cundinamarca, possibly because it is a less tourism-oriented region compared to Boyacá, as well as due to the dispersion of greenhouses and the rugged topography of the area.

At the level of identity, the landscape in both areas is perceived as an influential, unifying, and characteristic factor that shapes local idiosyncrasy. The landscape is valued as a competitive advantage for nature-based destinations, as noted by Clark et al. (2026), where the natural environment becomes a demanding factor for enterprises that must operate within sustainability thresholds. In this regard, Olwig (2002) emphasizes that natural landscapes evolve into cultural landscapes, in which geographical and ecological characteristics are integrated with human modifications, including built structures and land use (Cosgrove, 2008). However, in the study area, tensions have emerged associated with disruptions of the landscape matrix, fostering struggles for the conservation of natural landscape symbols and motivating producers' interest in transitioning toward sustainability.

In tomato cultivation, the adoption of agroecological practices (Wezel et al., 2009) promoted under tropical agriculture models (C. Jaramillo, 2019) can be identified. The regional approach seeks to replace chemical inputs with organo-mineral and biological sources. However, tomato producers continue to prefer chemical control for managing phytosanitary problems, despite promising experiences reported by those who use biopreparations, who indicate positive effects and reduced management costs.

**Figure 4.** Landscape change due to the presence of greenhouses for tomato production, Sutamarchán, Boyacá. Photograph: Diego Fernando Sánchez Vivas.

According to Tittonell (2019), agroecological transitions are multiscalar and multidimensional, and in tomato cultivation they remain incipient. Exogenous factors, such as the post-pandemic increase in chemical agro-input prices and the influence of environmental stakeholders, have fostered collective awareness of the risks associated with synthetic pesticides and have promoted agroecological practices (Torres-Carral, 2021).

Finally, another driving factor is the recognition of positive experiences in alternative management. Studies on organic matter sources, microorganism-based bioproducts, and agroecological management of greenhouse tomatoes report encouraging results, supporting the transition toward sustainable production models.

The analysis of the interactions component revealed a greater impact of tomato cultivation in Boyacá compared to Cundinamarca, mainly attributable to the productive trajectory of each region. In Boyacá, tomato cultivation has approximately 25 years of development, whereas in Cundinamarca the system has been implemented for about 17 years. Nevertheless, progress in the adoption of sustainable practices in both regions remains limited and has focused primarily on the use of bioproducts or biopreparations, largely driven by rising agrochemical prices.

# 4 Conclusions

Based on the 13 variables and 33 topics used in the socio-ecological analysis of protected tomato cultivation in the departments of Boyacá and Cundinamarca, 14 critical points affecting the production process were identified. In this way, the application of the socio-ecological systems framework is expanded to sustainable production, moving beyond its traditional use in analyzing conservation actions for natural resource management.

The two tomato-producing regions analyzed exhibit multiple similarities in social aspects and crop management practices. However, geographical and historical differences are decisive in explaining the contrasts observed in the resource system and resource components and in interactions. Boyacá, characterized by drier conditions and a longer trajectory in tomato production, has experienced greater incorporation of technological innovations over time. Nevertheless, this intensification has generated a more evident impact on the landscape and available natural resources.

Across both regions, the resource system and resource units component revealed the absence or lack of awareness of local conservation areas. In the governance component, private land ownership under smallholdings predominated, along with widespread disinterest among producers in consolidating and participating in local organizations. The actors and production system component showed that tomato cultivation is characterized by excessive use of chemically synthesized agro-inputs, loss of organic matter, permanent monocropping, and soil acidification, resulting in limited soil health. Finally, the interactions component reflected limited adoption of sustainable practices in tomato cultivation, together with high waste generation and abrupt landscape changes due to the expansion of greenhouse covers across the territory.

These findings suggest the need to focus efforts on: (a) strengthening local and regional conservation actions to ensure that water resources are maintained in Cundinamarca and not depleted in Boyacá; (b) fostering environmental awareness and social capital among smallholder tomato-producing families; (c) designing and implementing technologies that promote sustainable production, protect essential resources such as soil and water, reduce environmental impacts, and ensure greater food safety; (d) promoting the use of local materials in infrastructure, planting, and crop management to reduce dependence on external inputs; and (e) identifying and developing markets that value sustainable production, as the added value of differentiated production is currently not fully recognized.

It is recommended that future research apply the socio-ecological systems framework to the analysis of sustainable production deepen, through participatory approaches, the understanding of feedback loops that determine the main barriers to transitioning toward sustainability. This would support the definition of joint strategies among local, regional, and national actors to advance the consolidation of sustainable and resilient territories. Likewise, further research should explore cultural ecosystem services, beyond landscape aesthetics, to capture elements such as sense of belonging, identity, and connection with nature, among others.

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Earth Sciences

# Meteorological variability and its impact on agricultural activities in the Ecuadorian Amazon in Pastaza (2011–2021)

# Variabilidad meteorológica y su impacto en las actividades agropecuarias de la Amazonía ecuatoriana en Pastaza (2011–2021)

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**Abstract**

The climatic variability observed in Pastaza Canton has significantly affected agricultural and livestock productivity, compromising local food security. This study aims to analyze how climatic variables influence the main crops and livestock production between 2011 and 2021. An applied, non-experimental, descriptive-correlational, and cross-sectional methodology was used. Data were obtained from INAMHI meteorological records and the Public Agricultural Information System, considering variables such as mean temperature, total precipitation, relative humidity, and potential evaporation. Results showed that average monthly temperatures (20.63 °C–22.06 °C) were favorable for banana and cassava but below the optimal range for cocoa. Total precipitation reached 508.70 mm in May, causing waterlogging in coffee and sugarcane crops, whereas September (285.35 mm) showed water deficits. Relative humidity levels (85.00 %–89.36 %) increased fungal disease incidence and management costs, while potential evaporation (54.16 mm–89.57 mm) reduced soil moisture, affecting pineapple crops. In livestock systems, June and July presented favorable thermal conditions, and balanced evaporation in February maintained adequate pasture availability. Overall, banana and cassava exhibited greater adaptation to climatic variability, while cocoa, coffee, sugarcane, and pineapple showed productivity reductions associated with irregular rainfall and high humidity.

***Keywords***: Evaporation, livestock, humidity, precipitation, resilience.

**Resumen**

Las variaciones en las condiciones climáticas del cantón Pastaza han generado efectos significativos en la productividad agrícola y ganadera, comprometiendo la seguridad alimentaria local. El propósito del estudio es analizar cómo las variables climáticas influyen sobre los principales cultivos y la producción pecuaria entre 2011 y 2021. Se aplicó una metodología de tipo aplicada, con diseño no experimental, nivel descriptivo-correlacional y enfoque transversal. Los datos se obtuvieron de registros meteorológicos del INAMHI y del Sistema de Información Pública Agropecuaria, considerando variables como temperatura media, precipitación total, humedad relativa y evaporación potencial. Los resultados revelaron temperaturas promedio mensuales entre 20,63 °C y 22,06 °C, adecuadas para el plátano y la yuca, pero inferiores al rango óptimo del cacao. La precipitación alcanzó 508,70 mm en mayo, generando encharcamiento en café y caña de azúcar, mientras que en septiembre (285,35 mm) se observó déficit hídrico. Los niveles de humedad relativa (85,00 %–89,36 %) incrementaron la incidencia de enfermedades fúngicas y los costos de manejo, mientras que la evaporación potencial (54,16 mm–89,57 mm) redujo la humedad del suelo, afectando cultivos como la piña. En la ganadería, los meses de junio y julio presentaron condiciones térmicas favorables y evaporación equilibrada, manteniendo la disponibilidad de pastos. Se concluye que el plátano y la yuca mostraron mayor adaptación a la variabilidad climática, mientras el cacao, café, caña de azúcar y piña evidenciaron reducciones en productividad asociadas a lluvias irregulares y humedad elevada.

***Palabras clave***: Evaporación, ganadería, humedad, precipitación, resiliencia.

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# 1 Introduction

According to the World Meteorological Organization, climate is defined as the average and variability of meteorological variables such as temperature, precipitation, and wind in a specific region over a 30-year period (Rosvold, 2021). At the global level, meteorological conditions have shown significant fluctuations, with an increase of 0.74 °C in the global mean temperature over the last century (Shah et al., 2019). These variations have generated relevant impacts on agriculture, where drought accounts for more than 80 % of total damage and losses in the agricultural sector, particularly affecting livestock and crop production subsectors (Hernández et al., 2018).

At the regional level, meteorological fluctuations have caused reductions ranging from 20 % to 40 % in cereal and legume yields due to water stress, while crops such as rice have experienced losses of up to 92 % under extreme drought conditions (Kumar et al., 2022; Lal, 2021). In Colombia, environmental conditions between 2010 and 2011 led to the loss of 1,000,000 hectares of crops, with a total economic impact on the agricultural sector estimated at USD 759.893 million, including the death of 160,965 production animals (Arteaga and Burbano, 2018).

Ecuador, known for its climatic and productive diversity, faces increasing challenges in the agricultural sector due to variability and changes in meteorological conditions (García-Rengifo and Durán-Ballén, 2023). According to Vásquez-Dávila and Bravo-Benavides (2023), the relationship between temperature, precipitation, and agricultural production is significant, with long-term impacts if these variables exceed optimal levels.

In the case of Pastaza canton, which largely depends on agricultural activities, climate variability has caused fluctuations in agricultural yields, affecting productivity and the economic sustainability of rural communities. Therefore, it is necessary to identify, analyze, and understand climatic variables in order to predict how meteorological conditions have evolved (Singh et al., 2023). This will make it possible to propose specific adaptation measures that are essential to mitigate negative impacts on agricultural activities. In addition, it is currently necessary to design strategies that strengthen agricultural resilience and ensure economic and food sustainability (Sgroi, 2023).

Agricultural producers in Pastaza canton will be the main beneficiaries of studies on the variation of meteorological conditions and their impact on agricultural activities. Access to accurate information will allow them to adjust their management practices according to climatic conditions, thereby optimizing their production processes. Likewise, governmental and academic institutions will be able to use this information to plan and make strategic decisions in the agro-environmental field, facilitating the design of adaptation and mitigation strategies in response to climate change.

The main problem identified lies in the lack of precise data on climatic variations, which hinders the efficient management of agricultural activities in Pastaza province. Changes in precipitation patterns and increases in temperature have affected essential crops such as sugarcane, an important source of local income (Valle et al., 2021). Similarly, reduced pasture availability has negatively impacted livestock production, particularly dairy farming (Mosquera Ponce et al., 2024). According to Bilali et al. (2020), these climatic variations modify production cycles, increase production costs, and reduce yields, thereby compromising food security and the economic stability of small-scale producers.

Previous studies on this topic, such as that of Pujahari et al. (2022), who applied weather forecasting together with technologies such as the Internet of Things (IoT), wireless sensor networks, and machine learning, enabled farmers to optimize irrigation, fertilization, and pest control.

Meanwhile, Gowtham et al. (2018) supported meteorological predictions with advanced models such as the Decision Support System for Agrotechnology Transfer (DSSAT), contributing to more efficient and adaptive agricultural planning. Likewise, Ordoñez et al. (2022) developed agroclimatic models combined with seasonal forecasts, achieving 80 % accuracy in yield prediction and reducing climatic risk for farmers, which in turn improved productivity.

Based on the latter, the objective of this study is to analyze the variation of meteorological conditions and their impact on agricultural activities in Pastaza canton during the period 2011–2021.

## 2 Materials and Methods

The methodology was developed sequentially, beginning with the delimitation of the study area, the definition of the type of research, the determination of the study period, sample, and data sources, followed by data processing and statistical analysis. This methodological sequence ensures the replicability of the procedure and the verification of the results obtained.

### 2.1 Location

This study was conducted in Pastaza canton, at the facilities of the National Institute of Meteorology and Hydrology (INAMHI). This canton belongs to Pastaza Province, which covers an area of 29,643.33 km$^2$ and is bordered to the north by the provinces of Napo and Orellana, to the south by Morona Santiago, to the east by the Republic of Peru, and to the west by Tungurahua (Gobierno Provincial de Pastaza, 2020). This province is characterized by a humid tropical climate that favors agricultural activities and their analysis in relation to climatic variables (Figure 1).

### 2.2 Type of Research

The study adopted a quantitative approach with a non-experimental, descriptive-correlational, and cross-sectional design, which allowed for the examination of climatic variables in Pastaza canton during the analysis period (Cvetkovic-Vega et al., 2021). This design facilitated the analysis and description of climatic variables in Pastaza canton throughout the study period.

### 2.3 Study Period, Sample, and Data Source

The analysis was based on records covering the period from 2011 to 2021, corresponding to the most recent data available in the INAMHI archives. This time interval made it possible to identify interannual variations in climatic conditions and their relationship with agricultural activities in Pastaza canton.

The information was obtained from the "Pastaza" meteorological station (INAMHI), located at 1,060 m.a.s.l., selected due to the continuity and reliability of its records, as well as its representativeness of local agroclimatic behavior. As an accredited synoptic station, its measurements of temperature, precipitation, relative humidity, and potential evaporation comply with the technical accuracy standards established by the World Meteorological Organization (2021).

Quality control procedures were applied following the recommendations of the World Meteorological Organization (2010), including internal consistency checks, detection of extreme values using climatological thresholds, and cross-comparison with nearby stations and historical averages. Inconsistent records were verified and corrected or, when necessary, excluded from the analysis to ensure the integrity of the time series.

### 2.4 Variables Analyzed

The analysis of variables was conducted considering both climatic and agricultural aspects linked to productive activities in Pastaza canton. In the agricultural domain, variables such as planted area (ha), harvested area (ha), production (t), and yield (t/ha) of crops were included, as well as the total livestock population, considering cattle, swine, sheep, equine, and mule categories. These variables make it possible to understand the productive level and agricultural and livestock performance in the study area, which is essential for establishing their relationship with climatic variables.

Mean monthly temperature influences the physiological development of crops, as each species requires an adequate thermal range for growth. In addition, temperature affects livestock thermal comfort, where extreme variations can cause stress and reduce productivity (González Osorio et al., 2020).

Total monthly precipitation determines water availability for crops and forage, being necessary to ensure proper development. Water deficits limit growth and product quality, while excess precipitation can cause waterlogging and disease outbreaks (Paliz et al., 2021).

Mean monthly relative humidity favors the occurrence of phytosanitary diseases. High humidity levels promote the development of fungi and bacteria, reducing agricultural production quality (Pozo-Santiago et al., 2020).

Mean monthly potential evaporation directly influences irrigation water demand, since periods of high evaporation require greater water supply to prevent crop stress and ensure optimal development (Monterroso-Rivas and Gómez-Díaz, 2021).

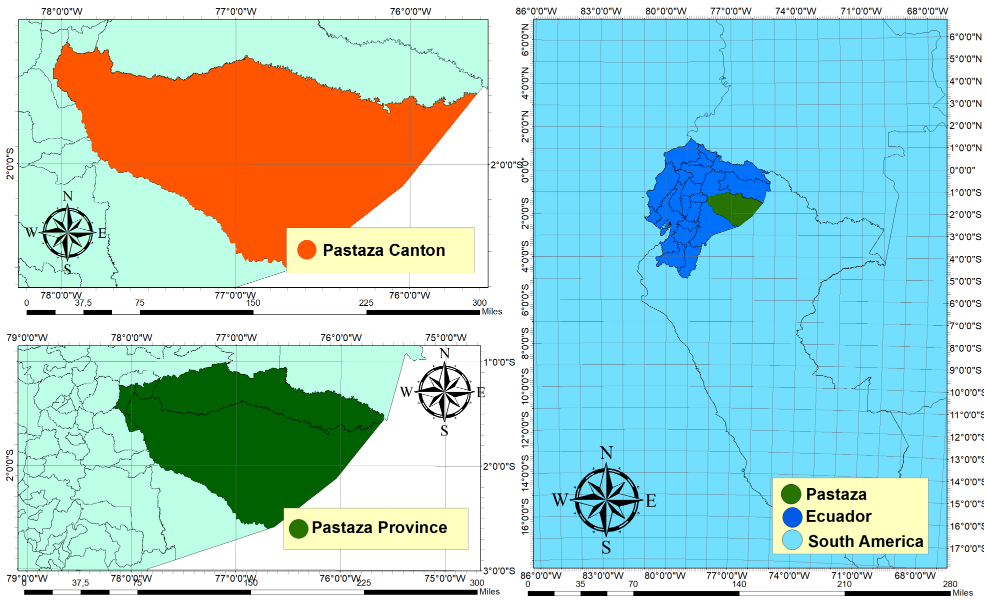


**Figure 1.** Geographical location of the study area.

## 2.5 Data Processing

Data processing included measures of dispersion and the coefficient of variation in order to quantify interannual variability. Statistical analysis was performed using Microsoft Excel® (version 2021) through Pearson correlations ($p < 0.05$) and simple linear regressions, applied only when the correlation coefficient $r$ exceeded 0.50 (50 %). In the absence of significant correlations, a comparative descriptive analysis between variables was conducted, allowing for the interpretation of local climatic behavior and its comparison with evidence from humid tropical regions.

## 2.6 Methodological Limitations

The study was based on records from a single meteorological station, which limits spatial analysis. The 11-year period represents an interannual scale that describes recent variability without reaching the temporal extent required for long-term climatic studies. Nevertheless, this approach is appropriate for characterizing local meteorological conditions and their influence on agricultural activities in Pastaza canton.

# 3 Results and Discussion

## 3.1 Agricultural Activities

According to the Sistema de Información Pública Agropecuaria (2024), the main agricultural activities correspond to plantain and cassava crops, which recorded the largest cultivated area and production during 2024 (Table 1). Plantain accounts for 3,439 ha planted, 2,554 ha harvested, and a production of 15,096 tonnes, with a yield of 5.91 t/ha. Cassava, with 1,999 ha planted and a production of 4,281 tonnes, reaches a yield of 2.21 t/ha. Pineapple stands out for its high yield of 9.86 t/ha, whereas crops such as cocoa and coffee show lower yield levels, with 0.30 and 0.58 t/ha, respectively.

**Table 1.** Production, cultivated area, and yield of agricultural crops during 2024.

| Product | Planted Area (ha) | Harvested Area (ha) | Production (t) | Yield (t/ha) |
|---|---|---|---|---|
| Plantain | 3,439 | 2,554 | 15,096 | 5.91 |
| Cassava | 1,999 | 1,937 | 4,281 | 2.21 |
| Dry hard maize | 282 | 282 | 253 | 0.90 |
| Sugarcane for other uses | 192 | 183 | 1,044 | 5.71 |
| Pineapple (fresh fruit) | 166 | 125 | 1,231 | 9.86 |
| Cocoa | 110 | 61 | 19 | 0.30 |
| Coffee | 69 | 69 | 40 | 0.58 |
| Banana | 64 | 64 | 273 | 4.28 |
| Peanut (shelled grain) | 49 | 49 | 27 | 0.55 |
| Lemon (fresh fruit) | 40 | 35 | 51 | 1.45 |
| Orange | 35 | 35 | 61 | 1.75 |
| Fresh bean | 11 | 11 | 11 | 0.95 |

According to the Sistema de Información Pública Agropecuaria (2024), cattle, with 3,722,314 animals, represent the largest population within the livestock sector. This is followed by swine, with 983,999 animals, and sheep, with 561,949. Equines are divided into horses, with 143,310 animals, and mules, which constitute the smallest proportion with 54,044 animals (Table 2).

**Table 2.** Livestock population during 2024.

| Livestock type | Number of animals |
|---|---|
| Cattle | 3,722,314 |
| Swine | 983,999 |
| Sheep | 561,949 |
| Horses | 143,310 |
| Mules | 54,044 |

*Source: Sistema de Información Pública Agropecuaria (2024).*

## 3.2 Influence of Mean Temperature on Agricultural Activities

Plantain has an optimal temperature range of 22 °C to 30 °C and can develop under temperatures between 20 °C and 35 °C (Zambrano et al., 2021). In Pastaza, mean monthly temperatures (20.63 °C to 22.06 °C) are very close to the lower limit of the optimal range (Figure 2). Months such as May (21.45 °C) and September (21.58 °C) are ideal for this crop, as they favor pseudostem growth and fruit filling (Cedeño García et al., 2021). Even in months such as June (20.94 °C) and October (21.99 °C), temperatures do not represent a significant threat to crop development, and no evident negative impact on plantain is observed. The average temperatures in Pastaza are adequate to sustain the current yield of 5.91 t/ha, indicating regular crop development.

Cocoa thrives within an optimal temperature range of 24 °C to 28 °C and tolerates temperatures from 15 °C to 32 °C (Ferrer-Sánchez et al., 2022). In Pastaza, mean monthly temperatures (20.63 °C to 22.06 °C) are below the optimal range but still within the tolerable range (Figure 2). This mismatch may slightly limit flowering and fruit set (Garay-Peralta et al., 2024). Months such as April (21.62 °C) and September (21.58 °C) provide relatively better conditions for cocoa development, although they do not reach the required optimal range. Cocoa shows a moderate impact due to temperatures that do not reach optimal levels, as reported by Castillo et al. (2024). This explains its low yield of 0.30 t/ha, and although the crop can survive under these conditions, its productivity remains far from ideal.

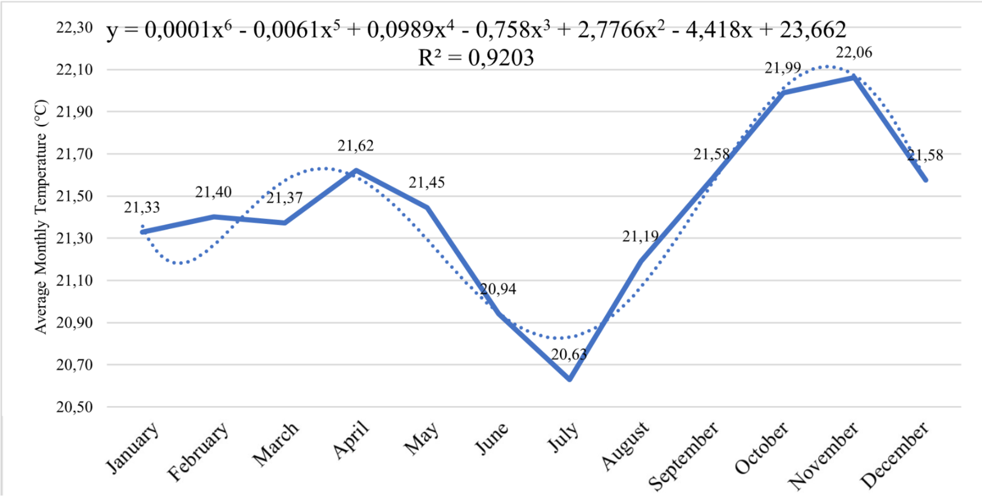


**Figure 2.** Average monthly temperature during the period 2011–2021.

Cassava thrives within an optimal temperature range of 25 °C to 29 °C and tolerates temperatures from 18 °C to 35 °C (Rosero et al., 2024). In Pastaza, all mean monthly temperatures (20.63 °C to 22.06 °C) fall within the tolerable range, although slightly below the optimal range. This implies that the crop can develop adequately throughout the year (Monsanto et al., 2020). Months such as February (21.40 °C) and April (21.62 °C) are particularly favorable, as they approach the lower limit of the optimal range (Figure 2). No significant negative impact on cassava yield is observed, as temperatures remain within the tolerable range. The current yield of 2.21 t/ha is consistent with these climatic conditions. However, temperatures closer to the optimal range could slightly increase productivity.

Livestock production, dominated by cattle with 3,722,314 animals, also shows a critical dependence on temperature. Warmer months such as October (21,99 °C) and November (22.06 °C) generate thermal stress in livestock, affecting feed intake and productivity, as reported by Midence and Blas (2024). Conversely, cooler temperatures in June (20.94 °C) and July (20.63 °C) may limit the growth of natural pastures (Cárdenas and Telles, 2023), reducing the availability of essential forage for livestock feeding.

The spatial and temporal variability of precipitation in Pastaza indicates a pattern highly dependent on topography and vegetation cover, generating contrasts between lowland and piedmont areas. This behavior is consistent with Cargua et al. (2024), who point out that local climatic gradients condition soil response and environmental stability in Amazonian and Andean regions. Similarly, Hidalgo et al. (2024) showed that changes in rainfall and temperature directly influence hydrological and ecological processes in mountainous environments. In the agricultural context of Pastaza, these variations determine water availability for plantain, cassava, and cocoa crops.

## 3.3 Precipitation Variability and Its Effect on Crops in Pastaza

Sugarcane depends on a constant water supply, ideally between 1,500 and 2,500 mm annually, distributed uniformly (Díaz Serna, 2024; Espinel Rubio and Feo-Ardila, 2022). In Pastaza, months such as May (508.70 mm) and April (450.94 mm) ensure adequate water levels for sucrose accumulation in the stalks (Figure 3). However, drier months such as September (285.35 mm) may affect crop growth and yield. This is consistent with Misra et al. (2020), who emphasize that rainfall irregularity generates water stress in high water-demand crops such as sugarcane.

Precipitation in Pastaza is adequate during the wet months; however, its irregular distribution limits the average sugarcane yield to 5.71 t/ha. According to Santiago Zárate et al. (2021), the average yield per hectare of sugarcane is 8.26 tonnes, with a maximum recorded value of 16.54 tonnes. This indicates that the implementation of supplemental irrigation systems and optimized agricultural practices could significantly contribute to improving the yield of this crop.

Pineapple thrives under annual precipitation ranging between 1,000 and 1,500 mm, with monthly requirements of 50 to 125 mm (Aguilera-Arango et al., 2022). In Pastaza, months such as April (450.94 mm) and May (508.70 mm) greatly exceed this monthly range (Figure 3), which may lead to excessive vegetative growth and delayed flowering, as noted by Bonet-Pérez et al. (2021). Likewise, relatively drier months such as July (314.90 mm) and September (285.35 mm) also exceed the maximum monthly threshold required for this crop.

Precipitation in Pastaza, although sufficient in quantity, exceeds the optimal levels recommended for pineapple cultivation during all months analyzed (Figure 3). This excess significantly affects yield, which stands at 9.86 t/ha, whereas Vélez-Izquierdo et al. (2020) report an expected average yield of 20 t/ha for this crop. Therefore, it is necessary to implement water management measures such as efficient drainage systems and controlled irrigation strategies to mitigate the effects of excess water and optimize crop conditions, thereby favoring an increase in yield.

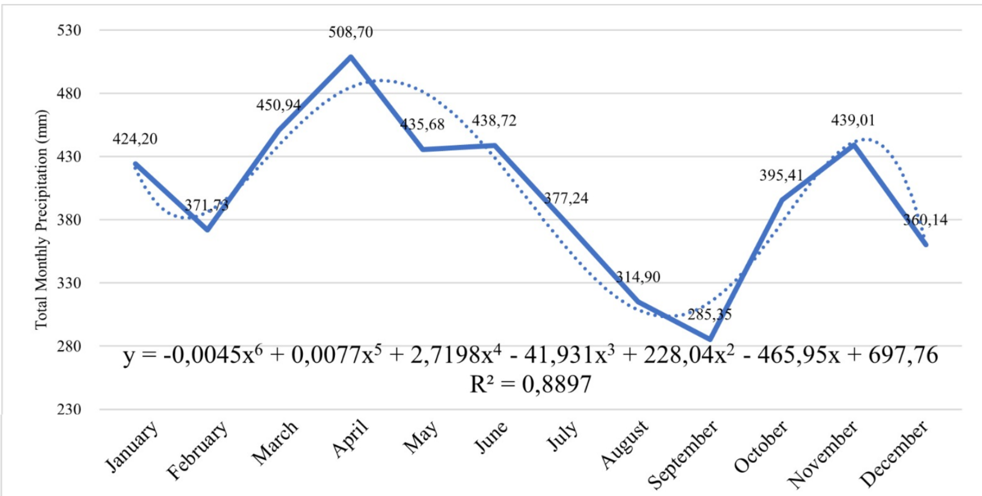


**Figure 3.** Total monthly precipitation during the period 2011–2021.

Coffee requires annual precipitation between 1,200 and 2,000 mm, with uniformly distributed rainfall and ideal monthly values of 100 to 200 mm to avoid prolonged water stress (Parada-Molina, Cervantes-Pérez, et al., 2020). In Pastaza, months such as May (508.70 mm) and November (439.01 mm) considerably exceed the optimal monthly range (Figure 3), which may cause waterlogging problems and affect bean quality (Quiroz Guerrero et al., 2024). Conversely, drier months such as July (314.90 mm) and September (285.35 mm), although still above the upper ideal monthly limit, meet the minimum water requirements of the crop.

Precipitation levels in Pastaza exceed the optimal monthly range for coffee in all months analyzed, generating a negative impact on bean quality due to excess moisture. This explains the low yield of 0.58 t/ha, consistent with Parada-Molina, Gómez Martínez, et al. (2020), who state that excessive rainfall can interfere with grain filling and reduce quality.

Pasture growth requires an optimal precipitation range between 300 and 400 mm per month (Brenes Gamboa, 2018). In Pastaza, although months such as May (508.70 mm) and November (439.01 mm) exceed this range (Figure 3), others such as September (285.35 mm) are at the lower threshold, which may affect forage production. These variations in water availability increase operational costs due to the use of feed supplements and reduce livestock profitability (Viera González et al., 2023).

Precipitation in Pastaza maintains adequate levels for agricultural production; however, its irregular distribution generates differentiated impacts depending on crop type. Prolonged intense rainfall favors the water accumulation required for sugarcane but exceeds the optimal requirements of pineapple and coffee, causing losses in flowering and bean quality. This behavior is consistent with Mestanza Uquillas et al. (2025), who demonstrated that the alternation between dry and rainy seasons on the central coast of Ecuador modifies crop productivity according to the rainfall regime and species adaptability. Complementarily, Quiroz Antunez et al. (2022) showed that irregular rainfall availability alters the suitability of coffee and cocoa crops under climate variability scenarios, affecting their phenological development. Consequently, the stability of agricultural production in Pastaza depends on efficient water management that allows compensation for the effects of pluviometric variability on local productivity.

## 3.4 Relative Humidity in Agricultural Productivity in Pastaza

Mean monthly relative humidity in Pastaza ranges between 85.00 % and 89.36 %, generating significant impacts on crops and livestock (Figure 4). During months with higher relative humidity, such as March (89.36 %) and April (88.40 %), the incidence of fungal diseases such as *Moniliophthora perniciosa* and *Hemileia vastatrix* increases in crops such as cocoa and coffee (Santiago-Elena et al., 2020). According to Mamani-Huayhua et al. (2021), these pathogens directly affect productivity. This negative impact occurs because higher relative humidity creates an optimal environment for the development and dispersal of these organisms (Lopez et al., 2021). The main implication lies in increased phytosanitary management costs and reduced agricultural yields, thereby compromising the economic sustainability of local farmers.

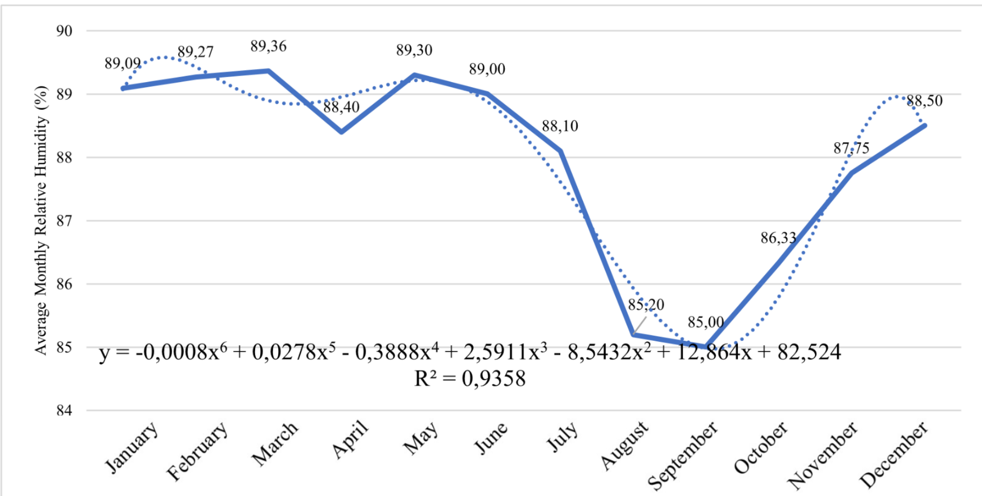


**Figure 4.** Average monthly relative humidity during the period 2011–2021.

In contrast, during months with lower relative humidity such as September (85.00 %) and October (86.33 %), humidity levels decline to the minimum tolerable threshold for most crops (Figure 4). Although this reduces the risk of certain fungal diseases, it does not completely eliminate their presence. According to Duran et al. (2021), these decreases may generate problems associated with water stress in humidity-sensitive crops, affecting their growth. Therefore, while crops benefit from lower relative humidity levels, adequate management is still required to mitigate adverse effects on productivity.

In livestock systems, high relative humidity promotes the occurrence of respiratory, dermal, and parasitic infections in animals such as cattle and swine. These problems tend to occur between March and June, when relative humidity levels consistently exceed 88 % (Figure 4). According to Conejo-Morales and Wing Ching (2020), these adverse conditions are due to moisture accumulation in pens, which hinders ventilation and increases ammonia levels in the air. The main implication of this phenomenon is a reduction in feed intake, leading to lower animal productivity and higher operational costs due to veterinary treatments and dietary supplements.

Months with lower relative humidity, such as September and October, provide some relief for livestock systems by reducing respiratory infections and moisture levels in pens (Figure 4). However, these conditions may also limit pasture growth, a primary source of feed for livestock. According to Alvarado Irías and Colon García (2023), this implies that although animals experience less thermal stress, producers face the challenge of compensating for reduced natural forage availability with supplemental feed, thereby increasing costs.

The high relative humidity values observed in Pastaza confirm a persistent atmospheric condition that favors the development of fungal diseases and the proliferation of microorganisms that affect both plant and animal physiology. According to Bibi and Rahman (2023), this type of environment limits leaf transpiration and alters metabolic processes in crops, reducing photosynthetic efficiency. In agreement, Vásquez et al. (2024) showed that under tropical conditions, relative humidity levels above 85 % increase the incidence of pests and diseases, reducing the productive stability of agricultural systems. Therefore, controlling relative humidity through microclimatic management practices and controlled ventilation in cultivated areas emerges as a viable alternative to reduce losses and maintain agricultural sustainability in the Ecuadorian Amazon region.

## 3.5 Potential Evaporation and Water Availability for Crops in Pastaza

Mean monthly potential evaporation in Pastaza ranges from 54.16 mm in February to 89.57 mm in September (Figure 5). High evaporation increases soil moisture loss, significantly reducing water availability for crops such as plantain, cassava, sugarcane, and pineapple. During August and September, when values exceed 80 mm, farmers increased irrigation requirements to maintain adequate soil moisture levels. According to Misra et al. (2020), high evaporation can limit crops' ability to absorb nutrients and carry out key processes such as photosynthesis, resulting in lower yields.

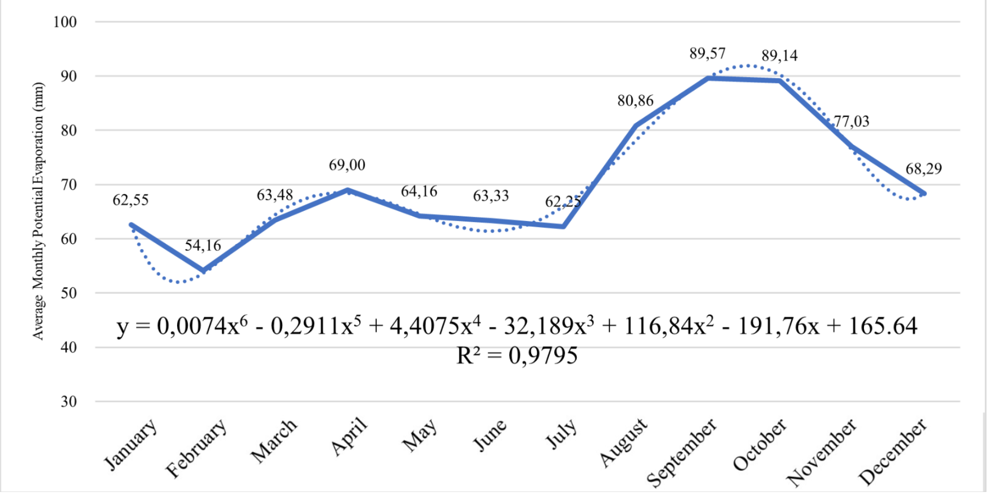


**Figure 5.** Average monthly potential evaporation during the period 2011–2021.

In sugarcane, this phenomenon directly affects sucrose accumulation in the stalks, reducing both quality and productivity. Similarly, in pineapple, water stress caused by elevated evaporation can delay flowering and reduce fruit size (Coelho et al., 2024). These effects highlight the need for advanced water management techniques, such as drip irrigation, to optimize the use of this limited resource during critical periods.

According to Srivastava et al. (2021), integrated water management is essential to mitigate these conflicts. Strategies such as rainwater harvesting, the use of efficient irrigation technologies, and the implementation of storage systems can help balance the needs of both sectors. In addition, sustainable agricultural practices, such as soil cover and the use of drought-resistant crops, can reduce dependence on additional water resources, thereby improving the overall sustainability of agricultural activities in Pastaza.

The evaporation dynamics in Pastaza show a relationship with solar radiation and vegetation cover, factors that modulate effective water availability in the soil. According to Arias-Muñoz et al. (2025), thermal variability and radiation intensity directly affect the water balance in Amazonian ecosystems, determining evaporation rates and surface moisture retention. In combination with the findings of Misra et al. (2020), increased evaporation reduces the capacity of crops to maintain the necessary root-zone moisture, affecting physiological processes such as transpiration and nutrient assimilation.

## 3.6 Regression Models of Climatic Variables

The regressions applied to climatic variables exhibit sixth-order polynomial behavior that adequately describes the monthly variation of meteorological conditions recorded in Pastaza canton during the period 2011–2021 (Table 3). The results indicate that the variables present a non-linear trend, mainly determined by seasonal cycles and atmospheric factors characteristic of tropical regions.

**Table 3.** Polynomial regression models of climatic variables in Pastaza (2011—2021).

| Climate variable | Polynomial regression equation (6th order) | $R^2$ | Figure |
|---|---|---|---|
| Mean monthly temperature (°C) | $y = 0.0001x^6 - 0.0061x^5 + 0.0989x^4 - 0.758x^3 + 2.7766x^2 - 4.418x + 23.662$ | 0.9203 | Fig. 2 |
| Total monthly precipitation (mm) | $y = -0.0045x^6 + 0.0077x^5 + 2.7198x^4 - 41.931x^3 + 228.04x^2 - 465.95x + 697.76$ | 0.8897 | Fig. 3 |
| Mean monthly relative humidity (%) | $y = -0.0008x^6 + 0.0278x^5 - 0.3888x^4 + 2.5911x^3 - 8.5432x^2 + 12.864x + 82.524$ | 0.9358 | Fig. 4 |
| Mean monthly potential evaporation (mm) | $y = 0.0074x^6 - 0.2911x^5 + 4.4075x^4 - 32.189x^3 + 116.84x^2 - 191.76x + 165.64$ | 0.9795 | Fig. 5 |

Overall, the identified trends confirm that climatic fluctuations in Pastaza do not respond to simple linear relationships, but rather to polynomial behaviors that better represent local atmospheric dynamics. These results are consistent with Shah et al. (2019), who explain that solar radiation and atmospheric pressure in tropical regions generate complex variations that hinder the application of linear models. In this context, it is recommended to complement the analysis with stochastic or machine learning approaches to capture non-deterministic patterns in climatic variability (Gowtham et al., 2018; Pujahari et al., 2022).

## 3.7 Monthly Impact of Climatic Factors on Crops

During January and October, soil saturation due to high humidity and intense rainfall affects crops such as sugarcane and plantain. This is consistent with Arias-Muñoz et al. (2025), who project a 14.65 % reduction in sugarcane cultivated area by 2031 as a consequence of environmental and climatic pressure. In April, high humidity and temperature favor the proliferation of fungi and bacteria in tropical fruits such as cocoa, a situation that would intensify under Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5 due to increased extreme precipitation and temperature (Serrano-Vincenti et al., 2025).

From June onward, an initial and progressive water deficit is observed, affecting crops such as plantain, sugarcane, and cassava. This pattern is consistent with Cachipuendo et al. (2025), who warn about the vulnerability of agricultural systems to reduced water availability resulting from the loss of water retention capacity. In addition, September presents a risk of asynchronous flowering due to irregular precipitation, affecting the phenological synchronization of cocoa. Finally, December shows a higher incidence of pests, in line with Meza et al. (2020), where climatic warming intensifies the reproduction of pathogens and pests in traditional agricultural systems. These effects validate the need for local climate adaptation strategies, especially in areas with diversified production and limited irrigation infrastructure.

**Table 4.** Relationship between monthly climatic conditions, type of impact, and sensitive crops.

| Month | Climatic Factor | Type of Impact | Potentially Affected Crops |
|---|---|---|---|
| January | High humidity + intense rainfall | Soil saturation | Sugarcane, cassava, plantain |
| February | High humidity + low radiation | Reduced photosynthesis | Cocoa |
| March | Excess rainfall | Waterlogging, erosion | Orange |
| April | High humidity + high temperatures | Proliferation of diseases | Cocoa |
| May | Moderate rainfall | Favorable vegetative development | Maize, cassava |
| June | Lower relative humidity | Initial water deficit | Plantain, sugarcane, cassava |
| July | Low precipitation | Progressive water stress | Pastures |
| August | Moisture deficit + high radiation | Wilting, yield reduction | Cassava, plantain |
| September | Irregular precipitation | Risk of asynchronous flowering | Cocoa |
| October | Increased rainfall | Soil saturation | Sugarcane, cassava |
| November | High humidity and cloudiness | Reduced maturation | Cocoa |
| December | Intense rainfall and heat | Increase in pests and fungi | Plantain |

# 4 Conclusions

Mean monthly temperature remained between 20.63 °C and 22.06 °C, a range favorable for crops such as plantain and cassava, although below the optimum for cocoa, which limits its productivity. Total monthly precipitation reached maximum values in April and May (450–470 mm), favoring sugarcane development but increasing the risk of waterlogging in sensitive crops such as coffee. The decrease in rainfall during September and October reduced water availability, affecting forage production and the sustainability of livestock systems.

High relative humidity levels (85 %–89 %) increased the incidence of fungal diseases in cocoa and coffee, generating higher management costs, while in livestock systems an increase in respiratory diseases was observed. Finally, potential evaporation, which reached its maximum in September (89.57 mm), highlighted the need for water management strategies and soil moisture conservation practices to prevent water stress.

# Author Contributions

**B.T.L.Z.:** Conceptualization, Formal analysis, Data curation. **J.M.M.V.:** Writing – original draft, Methodology, Investigation. **R.D.V.P.:** Writing – review and editing, Validation.

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# Quantitative analysis of crop richness and monoculture adoption in Ecuador

# Análisis cuantitativo de la riqueza de cultivos y la adopción de monocultivos en el Ecuador

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**Abstract**

In tropical countries, traditional production systems have proved to be fairly productive whereas having a lower environmental impact than conventional agriculture. Nevertheless, factors such as the penetration of the market economy and the disruption of commercial agriculture are reported to have negative effects on agrodiversity of traditional systems. This paper analyzes the socioeconomic determinants of crop richness and monocropping among Ecuadorian farmers. Using data from the Living Standards Measurement Survey-2014, multivariate techniques were used to assess the factors influencing decisions on how many crops to grow and on the likelihood of adopting monocropping. The results show that the number of crops a household grows is larger for poor large indigenous households. In contrast, crop richness is smaller for more educated households receiving off-farm income and residing near a road. In terms of which kind of household is the most likely to engage in monocropping, this is a household that has off-farm work, uses pesticides, and is located next to a road. On the other hand, poor indigenous households have less odds to adopt monoculture. These results demonstrate the importance of diversified agrosystems for rural people in Ecuador and reflect that policy makers should focus on the rescue and promotion of traditional agrosystems as a way to reach food security while promoting sustainable agriculture.

***Keywords***: Crop richness, monoculture, socioeconomic determinants, multivariate analysis, Ecuador.

**Resumen**

Los sistemas tradicionales de producción en países tropicales han demostrado ser relativamente productivos, al tiempo que tienen un menor impacto ambiental en comparación con la agricultura convencional. Sin embargo, la penetración de la economía de mercado y la irrupción de la agricultura comercial se reportan como factores que tienen un efecto negativo en la agrodiversidad de los sistemas tradicionales. Este artículo analiza los determinantes socioeconómicos de la riqueza de cultivos y adopción del monocultivo entre los agricultores ecuatorianos. Los datos corresponden a la Encuesta de Condiciones de Vida-2014, y se usaron técnicas multivariadas para evaluar los factores que influyen en las decisiones de cuántos cultivos producir y la probabilidad de adopción del monocultivo. Los resultados muestran que el número de cultivos que produce un hogar es mayor para los hogares pobres y numerosos que son liderados por indígenas. Por otra parte, la riqueza de cultivos es menor para los hogares con mayor educación, que tienen empleo fuera de la finca y residen cerca de una carretera. En términos de qué tipo de hogar tiene mayores probabilidades de incursionar en el monocultivo, este es un hogar que tiene empleo fuera de finca, usa pesticidas y se localiza cerca de una carretera. También, los hogares pobres con jefes indígenas tienen menores probabilidades de adoptar el monocultivo. Estos resultados demuestran la importancia que tienen los agrosistemas diversos para los habitantes de áreas rurales en Ecuador, y reflejan que los legisladores deberían enfocarse en la promoción y el rescate de los agrosistemas tradicionales como una estrategia para alcanzar la seguridad alimentaria y promover la agricultura sostenible.

***Palabras clave***: Riqueza de cultivos, monocultivo, determinantes socioeconómicos, análisis multivariado, Ecuador.

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# 1 Introduction

The expansion of conventional agriculture is reported to have negative environmental impacts (Ongley et al., 2010; Comoretto et al., 2008; Lambin et al., 2001). Therefore, many call for more sustainable production schemes (Holt-Giménez and Altieri, 2013). In many tropical countries, traditional production systems are essential to maintain food security and the livelihoods of rural people, as they have proved to be reasonably productive while being more environmentally friendly (Coq-Huelva et al., 2018; Torres et al., 2015). One of the key features of diversified systems is their high level of plant diversity in the form of polycultures and agroforestry systems.

Maintaining crop biodiversity is a deliberate strategy used by farmers to reduce risks, stabilize crop yields, promote diet diversity, and maximize returns even with low access to modern technologies and resources (Altieri, 2009, 2002). Diversity of crops and trees in traditional agroecosystems promote the recycling of nutrients; improves the use of water, nutrients, and sunlight; reduces the incidence of pests and weeds; and allows farmers to produce in a variety of agroecosystems with different soils and agroclimatic conditions (Holt-Giménez and Altieri, 2013; Abebe, 2013; Altieri et al., 2012).

While traditional systems have proved to be resilient and have stood the test of time (Altieri et al., 2012), a number of factors, including market penetration, migration, population growth, land fragmentation, political changes, agricultural modernization, among others, may have a negative effect on crop diversity. Relatively few case studies have focused on analyzing the socioeconomic factors affecting crop diversity in tropical countries. For instance, in Ethiopia, Abebe (2013) found that proximity to markets exerts a negative effect on crop diversity, as farmers residing near markets prefer to specialize in the production of cash crops that can be easily marketed, and to purchase other products they need for household consumption from the market. In the Ecuadorian Amazon, Torres et al. (2018) found that households that obtain their livelihood principally from livestock production and off-farm employment grow fewer crops than those for whom agriculture is their main livelihood activity. In addition, the authors reported that households accessible by road tend to exhibit low levels of crop diversification.

In Malawi, Fatch et al. (2020) determined that households receiving off-farm income are less diversified than those obtaining their income only from agricultural activities. The authors argue that this is because households engaged in off-farm work lack the labor force required to maintain a diversified farm. In their study in Indonesia, Abdoellah et al. (2006) reported that crop diversification has decreased as many households engage in monoculture, switching from subsistence to commercial agriculture. Prior research also reveals that indigenous peoples tend to keep highly diversified impact (Perrault-Archambault and Coomes, 2008; Torres et al., 2018; Abril Saltos et al., 2016) home gardens and to use agricultural practices with low environmental; nevertheless, recent evidence (Vasco, Torres, et al., 2021) reflects that indigenous peoples also engage in unsustainable agricultural practices (i.e., forest clearing, monocropping, cattle ranching, use of chemicals) when in contact with the market economy.

Using data from the Living Standards Measurement Survey 2013-2014, this paper adds up to the existing literature by examining the socioeconomic determinants of crop diversity -proxied by the number of crops a household has produced- and the likelihood of monocropping adoption in rural Ecuador. As for the rest of this paper, it is structured as follows: Section 2 describes Ecuador in terms of its geographic regions and its agricultural patterns, Section 3 describes the survey and explains the statistical methods, Section 4 presents and discusses the results, while Section 5 concludes.

# 2 The context: Agriculture in Ecuador

The agricultural sector is important for the Ecuadorian economy. It accounts for 8 % of the country's GDP and for around 42 % of non-oil exports, with bananas, cocoa, coffee, fresh flowers and fruits being the principal exportable products (BCE, 2019). Agriculture is the main economic activity for around 48 % of the rural population, with earnings from agriculture accounting, on average, for around 40 % of rural households' income (Vasco


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and Tamayo, 2017; INEC, 2010). Despite these figures, conventional agriculture has also been reported to have negative environmental effects, including the advance of the agricultural frontier and non-point source pollution (Wunder, 2001). Land concentration is an issue, with a Gini coefficient of 0.8 and 63.5 % of the farms smaller than 5 ha (Brassel et al., 2010). Many of those farms exhibit a high degree of biological diversity in the form of polycultures and agroforestry systems, and, while small, support peasant families and provide 64 % of the country's agricultural production (FAO, 2021).

Continental Ecuador is subdivided in three geographical regions: the coastal region (*la Costa*), the highlands (*la Sierra*) and the Amazon (*la Amazonía*). The marked differences in terms of landscape, ecosystems and sociocultural background determine agricultural patterns specific for each region (Intriago et al., 2017). To illustrate, the coastal region encompasses all the plains along the Pacific Ocean and the foothills of the Andes. It is characterized by lush vegetation combining dry and, to a lesser extent, evergreen forests, although an important part of the native vegetation has disappeared in favor of agricultural uses (MAE, 2013).

This region concentrates export-oriented agriculture, with large plantations of banana, cacao, and oil palm accounting for around 67 % of the area planted with perennial crops. This region also has important areas devoted to pastures and temporary crops, including rice, maize, and soybean (INEC, 2021). Despite the expansion of monoculture to produce agricultural commodities, many small-scale farmers still practice traditional agriculture and maintain farms with high levels of biodiversity, principally for self-consumption (Intriago et al., 2017).

*La Sierra* comprises the Andean territories. The region is highly heterogeneous in terms of altitude, topography, temperature, and soils (Hofstede et al., 1998). Agriculture is principally focused on the production of staples, including potatoes, maize, beans, and tuber crops, among others, although there are important areas -usually the plain and most fertile lands- devoted to the production of fresh flowers and broccoli for export (INEC, 2021). Agricultural income is the main income source for rural households accounting, on average, for 45 % households' total income in this region (Vasco and Tamayo, 2017).

Land concentration is more marked in the highlands than in the rest of Ecuador's geographical regions, with a Gini coefficient of 0.81. Unequal distribution of resources (i.e., land and irrigation water) threatens the livelihoods of many small-scale farmers, principally the indigenous population, who account for 20 % of the total rural population in the highlands (INEC, 2010). The *chakra andina* is the most common traditional system in the highlands. Widely used by indigenous populations, it is an agrosystem characterized by high levels of biodiversity, and a complex system of seed conservation and varietal adaptation at different altitudinal levels (2,400-3,500 m) (Intriago et al., 2017). Small-scale farmers practicing the *chakra andina* have been able to develop ingenious methods for the ecological management of soils, water, and genetic resources. Nevertheless, limited access to land and water, together with land fragmentation is reported to threaten the *chakra andina* (Gortaire, 2016), as, in some areas, farm sizes are too small to support and nourish rural families.

The Ecuadorian Amazon is one of the world's biodiversity hotspots. It is home to several indigenous peoples, who have long lived in the area and account for 47 % of the rural population, while the rest are principally mestizo-colonists who migrated from the coastal region and the highlands, starting in the 1960s (INEC, 2010). Agriculture is still an incipient activity due to the low fertility of soils, a poor road network and remoteness from the main agricultural markets (Vasco Pérez et al., 2015). Mestizo-colonists have usually engaged in unsustainable activities, including forest clearing, cattle ranching, and monocropping, as a consequence, deforestation rates in the territories controlled by colonists ranked as the highest among the Amazonian countries (Bilsborrow et al., 2004).

In contrast, indigenous peoples are reported to obtain their livelihood from subsistence agriculture and to use agricultural practices with low environmental impact (Nuckolls, 2010). Most indigenous peoples in the Amazon practice the *chakra amazónica*. This is a traditional agroforestry system featured by high levels of biodiversity that combines subsistence crops (e.g., plantains and cassava) with cash crops (e.g., cacao and coffee) and has proved to be successful in providing food and income to indigenous peoples while having a low environmental impact, as it normally does not require the use of external inputs (i.e., chemical fertilizers and pesticides) (Coq-Huelva et al., 2017). Although it is deeply rooted in the culture of Amazonian peoples, factors like the penetration of the market economy and the adoption of monocropping may be detrimental for the continuity of the *chakra amazónica* (Vasco, Torres, et al., 2021).

# 3 Methods

## 3.1 Data and variables

Data came from the Living Standards Measurement Survey 2013-2014 (LSMS 2013-2014) conducted by the National Institute of Statistics (INEC). This is a cross-sectional data set that has national representation and includes a full section about housing, household composition, health, education, household assets and economic activities for a total of 28,970 households (INEC, 2014). The survey also incorporates a section about agricultural activities, which includes information on landholding size, crop and animal production, yields, farm equipment and investments, which makes this survey useful for the objectives of this study. For the analysis, we selected the households that reported having produced at least one crop during the twelve months preceding the data collection. This resulted in a sample of 9,819 households distributed as follows: 5,619 households in the highlands, 1,942 in the coastal region and 2,258 in the Amazon[1].

The dependent variables of interest were crop richness, that is the number of crop species grown in a farm, and a binary variable taking the value of 1 if the household adopted monocropping and 0 otherwise (see Table 1 for definitions). Concerning independent variables, we included a number of household head and household predictors that are expected to have an effect on the dependent variables under study. The first group, household head predictors, include the age of the head and a binary variable taking the value of 1 if the household is a woman and 0 otherwise. Two binary variables taking the value of 1 whether the head defines himself/herself as indigenous or afro Ecuadorian, respectively, controls for the effect of ethnicity on the outcome variables under analysis. The group of people who define themselves as *mestizo* -the largest in the sample- is left as the comparison group. In addition, three binary variables taking the value of 1 if the household head is illiterate, had completed secondary education or held a university degree, respectively, are used to control for the role of education. Those who had completed only primary education are left as the baseline group. Prior research (Perrault-Archambault and Coomes, 2008; Torres et al., 2018; Abril Saltos et al., 2016) reported that these predictors exerted a significant effect on the number of crops in a farm.

At household-level, the household size and a binary variable taking the value of 1 has the household hired extra family labor control for labor force availability. Additionally, we include the number of internal and international migrants as these predictors may reduce the household labor for agricultural activities (Gray, 2009). Farm size and the area a household has rented during the twelve months preceding the survey controlled for land a household possesses or manages for farming. Overall, diversified agrosystems are reported to have a low environmental impact and to use low amounts of external inputs (Coq-Huelva et al., 2018). To test this hypothesis, a dummy variable was used, taking the value of 1 if the household has used pesticides during the twelve months prior data collection. Off-farm employment is expected to exert a negative effect on crop diversity as it takes household labor out of the farm, so that households engaged in off-farm work may lack the labor force to maintain a diversified farm (Fatch et al., 2020; Torres et al., 2018). To control this potential source of variance, our specification includes a binary variable taking the value of 1, which has the household receiving off-farm income.

[1]While the LSMS 2013-2014 includes households from the Galápagos islands (the insular region of Ecuador), we did not consider that region in the analysis here as the number of households involved in agricultural production (56) was too little to conduct multivariate analysis.

A wealth index[2], the number of heads of cattle a household possesses and a dummy taking the value of 1 whether or not the household is benefiting from the *Bono de Desarrollo Humano* social program[3], are used to proxy households' economic conditions. In a similar fashion, we also included a dummy indicating if the household has received a loan during the 12 months preceding the survey as a covariate. The role of road infrastructure on shaping decisions of how many species to grow is controlled by a dummy taking the value of 1 if the household is accessible by road. Finally, the model includes two binary variables indicating if the household is located in the *Costa* or the *Amazonia*, with the households located in the *Sierra* as the reference group.

## 3.2 Statistical Methods

We used multivariate regression to find the socioeconomic determinants of crop diversity and adoption of monoculture. It is worth noting, before proceeding, that there may be characteristics that are inherent to a specific area and are not considered in the model. Such contextual variables may shape households' decisions concerning how many crops to grow. Ignoring the hierarchical nature of the data may lead to wrong results and misleading interpretations. To control the hierarchical nature of the data, we used multilevel models. These kinds of models are commonly used in environmental sciences and are useful to control clustered sampling designs and to model contextual effects (Wikle, 2003). Hence, in the case of species richness, we relied on a multilevel linear model:

$$Y_{ij} = \alpha + X_{ij}\beta + \varepsilon_{ij} + u_j \qquad (1)$$

Where $Y$ is the number of crops that household $i$ in canton $j$ has grown in the twelve months preceding data collection, $\alpha$ is the intercept, $X$ is a vector of covariates that were listed and described above, $\beta$ is a vector of coefficients, the size and direction of which we are interested to know, $\varepsilon$ stands for the household level error term and $v$ is the error term at canton level.

As for the likelihood for a household to adopt monoculture, it was estimated using a multilevel logistic model:

$$Pr(Y_{ij} = 1|X_{ij}, u_j) = H(X_{ij}\beta + z_{ij}u_j) \qquad (2)$$

Where $Y$ is a binary variable taking the value of 1 if the household $i$ in the canton $j$ adopted monoculture, $X$ is a vector of the covariates already described, $u$ is a set of random effects at canton level, $H$ is the logistic cumulative distribution function $\beta$ is a vector of coefficients and $z$ are the covariates of the random effects. Since the coefficients of a logit model are not directly interpreted, in the section of results we present and discuss the marginal effects of each predictor.

# 4 Results

## 4.1 Crop richness

Column I in Table 2 shows the results of an ordinary least squares (OLS) regression with species richness as the dependent variable. There is a quadratic behavior with respect to the age of the household head, with the number of species grown increasing with age to a threshold at 53 years and then decreasing. Having a woman as the head reduces the number of crop species in 0.192. As expected, households having a head that defines himself/herself as indigenous increases the species richness in 0.588. In contrast, our results show that households with afro Ecuadorian heads grow fewer species than their mestizo counterparts.

In terms of the education predictors, the dummy variable accounting for having a university degree has a negative effect on the number of species. Holding a university degree reduces by 0.325 the number of crops grown by a household. Each new household member increases the number of crops produced by a household by 0.10. On average, households that have off-farm employment grow fewer crops than their counterparts not engaged in off-farm activities.

Households benefiting from the *Bono de Desarrollo Humano* grow more crops than their non-recipient peers. Receiving the BDH increases by 0.23, on average, the number of crops grown by a household. Proximity to roads has a negative effect

[2]The index was the main component of possession of a radio, TV, cell phone, computer, gas stove, refrigerator, car, and motorcycle. The first principal component explained 31 % of the variance.

[3]The *Bono de Desarrollo Humano* is a governmental conditional transfer granting US $ 50 to households living under the poverty line on the condition that the money is spent on health and education.

on species richness, with households located next to a road having, on average, 0.33 fewer crop species than those not served by a road system. Finally, the results reveal that there are geographical differences in terms of species richness. Households located in the coastal region grow, on average, 0.51 fewer species than their counterparts in the highlands.

**Table 1.** Descriptive statistics and variable definitions.

| Variable | Description | Mean | S.D. |
|---|---|---|---|
| **Dependent variable** | | | |
| Crop richness | Number of crops a household grows. | 3.811 | 2.838 |
| Monoculture | Household has adopted monoculture (0/1). | 0.138 | - |
| **Independent variable** | | | |
| Age | Age of household head (years). | 51.798 | 16.424 |
| Female | Household head is a woman (0/1). | 0.190 | - |
| Mestizo | Household head is mestizo (0/1). | 0.583 | - |
| Indigenous | Household head is indigenous (0/1). | 0.307 | - |
| Afro Ecuadorian | Household head is afro Ecuadorian (0/1). | 0.024 | - |
| Illiterate | Household head is illiterate (0/1). | 0.153 | - |
| Primary education | Household head has completed primary education (0/1). | 0.623 | - |
| Secondary education | Household head has completed secondary education (0/1). | 0.179 | - |
| University degree | Household head holds a university degree (0/1). | 0.043 | - |
| Household size | Household size. | 4.122 | 2.243 |
| Hired labor | Household has hired labor force (0/1). | 0.223 | - |
| Internal migrants | Number of internal migrants. | 0.196 | 0.707 |
| International migrants | Number of international migrants. | 0.021 | 0.239 |
| Landholding size | Farm size (ha). | 10.836 | 212.641 |
| Rented land | Amount of rented land (ha). | 1.920 | 112.765 |
| Pesticides | Household has used pesticides (0/1). | 0.438 | - |
| Off-farm employment | Household has off-farm employment (0/1). | 0.377 | - |
| Wealth index | Wealth index. | -0.012 | 1.710 |
| Cattle | Number of cattle the household owns. | 2.440 | 7.087 |
| Bonus | Household received *Bono de Desarrollo Humano* (0/1). | 0.589 | - |
| Credit | Household has received credit (0/1). | 0.127 | - |
| Road | Household is located next to a road (0/1). | 0.753 | - |
| Sierra | Household is located in the *Sierra* (0/1). | 0.572 | - |
| Costa | Household is located in the *Costa* (0/1). | 0.197 | - |
| Amazonia | Household is located in the *Amazonia* (0/1). | 0.229 | - |

Note: (0/1) identifies dummy variables. S.D.: Standard Deviation.

Columns II-IV present independent regressions for each region. While most of the coefficients remain unaltered, the landholding size becomes significant in the regression for *la Sierra*. In the case of the Coast, the dummy controlling for receiving the *Bono de Desarrollo Humano* is not significant anymore, while in the *Amazonia*, the effect of female headship is no longer significant.

## 4.2 Monoculture adoption

The results of a multilevel logit model are shown in Column I in Table 3. The likelihood of adopting monoculture grows with age to a threshold at 73 years and then declines. As expected, indigenous households are less likely to adopt monoculture. Having an indigenous head reduces the odds of adopting monoculture in 4 %. Household size has a negative effect on the likelihood of adopting monoculture. Each new member of a household increases the odds of monoculture in 0.7 %. Households using pesticides are 2.7 % more likely to practice monoculture.

Having off-farm income increases the likelihood of adopting monoculture in 2.8 %. Each head of cattle a household possesses reduces the likelihood of monoculture in 0.1 %. Contrary to the results for crop richness, receiving the *Bono de Desarrollo Humano* reduces the likelihood of practicing monoculture in 2.2 %. Households located next to a road are 4.4 % more likely to adopt monoculture. Consistent with the results for crop richness, households residing in the coastal region are 5.7 % more likely to engage in monoculture than their peers from the highlands. In contrast, Amazonian households are less likely to engage in monoculture. Residing in the Amazon reduces the likelihood of adopting monoculture in 5.5 %.

Whereas most of the coefficients remain unchanged when running independent regressions for each region (Columns II-IV), the dummy accounting for indigenous household head and the number of cattle is not significant anymore in the *Sierra*. The effect of age is no longer significant in the regressions for the Coast and the *Amazonia*.

**Table 2.** Socioeconomic determinants of crop richness (OLS).

| | Richness of crops | | | |
|---|---|---|---|---|
| **Variable** | **Overall (I)** | **Sierra (II)** | **Costa (III)** | **Amazonia (IV)** |
| Age | 0.070*** | 0.067*** | 0.083*** | 0.068*** |
| Age squared | -0.000*** | -0.000*** | -0.000*** | -0.000*** |
| Female (0/1) | -0.192*** | -0.146* | -0.413*** | -0.157 |
| Indigenous (0/1) | 0.588*** | 0.456*** | -0.518 | 0.762*** |
| Afroecuadorian (0/1) | -0.401** | -0.307 | -0.444** | -0.608 |
| Illiterate (0/1) | -0.042 | -0.012 | 0.014 | -0.066 |
| Secondary education (0/1) | -0.102 | -0.203 | 0.018 | 0.035 |
| University degree (0/1) | -0.325*** | -0.637*** | 0.065 | 0.097 |
| Household size | 0.102*** | 0.129*** | 0.052* | 0.078*** |
| Hired labor (0/1) | 0.486*** | 0.573*** | 0.363*** | 0.435*** |
| Internal migrants | -0.049 | -0.070 | 0.018 | -0.054 |
| International migrants | -0.003 | -0.073 | -0.105 | 0.217 |
| Landholding size | -0.000 | 0.005*** | -0.000 | 0.000 |
| Rented land | -0.000 | -0.008 | -0.000 | -0.004 |
| Pesticides (0/1) | 0.799 | 0.934 | 0.645 | 0.574 |
| Off-farm employment (0/1) | -0.566*** | -0.601*** | -0.369*** | -0.601*** |
| Wealth index | 0.017 | 0.020 | 0.059 | -0.040 |
| Cattle | 0.003 | 0.000 | -0.002 | 0.014* |
| Bonus (0/1) | 0.232*** | 0.283*** | 0.093 | 0.280*** |
| Credit (0/1) | 0.081 | 0.155* | -0.094 | -0.070 |
| Road (0/1) | -0.339*** | -0.232*** | -0.674*** | -0.341*** |
| Costa (0/1) | -0.524*** | - | - | - |
| Amazonia (0/1) | 0.199 | - | - | - |
| Intra-class correlation | 4.792*** | 3.187*** | 2.447*** | 3.125*** |
| Number of cantons | 659 | 348 | 187 | 124 |
| Number of observations | 9,819 | 5,619 | 1,942 | 2,258 |
| Wald test | 880*** | 586*** | 180*** | 204*** |

Note: *, ** and *** stand for significance at 10, 5 and 1 %, respectively. (0/1) identifies dummy variables.

**Table 3.** Socioeconomic determinants of monoculture adoption (logit).

| | Adoption of monoculture | | | |
|---|---|---|---|---|
| **Variable** | **Overall (I)** | **Sierra (II)** | **Costa (III)** | **Amazonia (IV)** |
| Age | 0.003** | -0.004*** | -0.000 | -0.000 |
| Age squared | -0.000** | 0.000*** | 2.61 | 2.61 |
| Female (0/1) | 0.001 | -0.012 | 0.002 | 0.002 |
| Indigenous (0/1) | -0.039*** | -0.014 | -0.057*** | -0.057*** |
| Afroecuadorian (0/1) | 0.008 | 0.097 | 0.017 | 0.017 |
| Illiterate (0/1) | 0.014 | 0.015 | 0.000 | 0.000 |
| Secondary education (0/1) | -0.003 | -0.006 | 0.007 | 0.007 |
| University degree (0/1) | 0.017 | 0.047* | -0.002 | -0.002 |
| Household size | -0.007*** | -0.000*** | -0.003* | -0.003* |
| Hired labor (0/1) | 0.025 | 0.001 | 0.004 | 0.004 |
| Internal migrants | -0.003 | 0.004 | -0.002 | -0.002 |
| International migrants | 0.012 | 0.017 | -0.001 | -0.001 |
| Landholding size | 0.000 | -0.000 | -0.000 | -0.000 |
| Rented land | -0.000 | 0.001 | -0.004 | -0.004 |
| Pesticides (0/1) | 0.027*** | 0.021*** | 0.016* | 0.016* |
| Off-farm employment (0/1) | 0.028*** | 0.020** | -0.001 | -0.001 |
| Wealth index | 0.000 | 0.001 | 0.002 | 0.002 |
| Cattle | -0.001** | -0.000 | -0.003*** | -0.003** |
| Bono (0/1) | -0.022*** | -0.032*** | -0.006 | -0.006 |
| Credit (0/1) | -0.006 | 0.002 | -0.004 | -0.004 |
| Road (0/1) | 0.044*** | 0.033*** | 0.027*** | 0.027*** |
| Costa (0/1) | 0.057*** | - | - | - |
| Amazonia (0/1) | -0.055*** | - | - | - |
| Intra-class correlation | 1.56*** | 1.75*** | 2.45*** | 1.98*** |
| Number of cantons | 659 | 348 | 187 | 124 |
| Number of observations | 9,819 | 5,619 | 1,942 | 2,258 |
| Wald test | 193*** | | | |

Note: *, ** and *** stand for significance at 10, 5 and 1 %, respectively. (0/1) identifies dummy variables.

# 5 Discussion

The data suggest that decisions of whether to maintain diversified farms or engage in monoculture are principally shaped by ethnicity, education endowment, labor force availability and poverty. In the case of ethnicity, the results show that indigenous people have more diversified farms. This finding is not surprising, since, as referred to earlier in section 2, indigenous peoples are reported to maintain agrosystems featured by high levels of biodiversity (Gortaire, 2016). This pattern occurs in the *Sierra* and the *Amazonia*, but not in the *Costa*, probably because indigenous population in that region is low (INEC, 2010). Surprisingly, the results show that indigenous peoples in the *Sierra* are as likely as their mestizo counterparts to engage in monoculture. This should be a source of concern due to the importance that indigenous agriculture has for the preservation and promotion of sustainable agriculture (Parraguez-Vergara et al., 2018). Indigenous populations in the *Amazonia*, however, are less likely to engage in monoculture, probably because of the social, cultural and economic importance that the *chakra* system has among indigenous peoples in the Amazon (Coq-Huelva et al., 2018). Afro Ecuadorian populations in the Coastal have less diversified farms than their mestizo counterparts, which suggest that they are more engaged in commercial agriculture.

While in the *Costa* and the *Amazonia* education does not exert any significant effect on crop richness and monoculture adoption, in the *Sierra*, households with heads having a university degree have less diversified farms. This may signify that more educated households engage in cash crop production and, therefore, have less diversified farms. Whereas increasing education in rural areas is considered a development priority, this finding reflects a negative externality of education with regards to promotion of sustainable agriculture, so policy makers should focus on developing curricula that emphasizes the importance of sustainable agriculture and diversified agrosystems (Vasco, Tafur, et al., 2021).

The findings reflect the labor force as a key element for maintaining diversified farms. Overall, larger households have more diversified farms and are less likely to engage in monoculture. Prior research (Vasco, Tafur, et al., 2021) has already shown that larger households, with more labor force, are able to maintain more crops. This is also consistent with the Chayanovian postulate that peasant agriculture, like the one practiced in traditional agrosystems, has been able to survive and even compete with modern agriculture, mainly relying on family labor force (Chayanov, 1966). Also related to labor force availability, the results show that farms growing more crops need to hire extra-household labor, which confirms that labor force is a key element -perhaps a bottle neck- for the development of sustainable agriculture. In this sense, policy makers should address their efforts to develop labor-saving technologies for small-scale farmers.

Households having off-farm work have less diversified farms. Three possible arguments arise to explain this finding. First, it is possible that such households have less labor force available for agricultural production, so that they cannot grow many crops in their farms (Torres et al., 2018). Second, it is also possible that farming is not a priority for these kinds of households as earnings from off-farm employment tend to be significantly higher than those to be obtained from agricultural production (Vasco and Tamayo, 2017). Third, it is likely that earnings from off-farm work are invested in conventional agricultural production (Angelsen and Kaimowitz, 2001).

Receiving the *Bono de Desarrollo Humano* is positively correlated with crop richness and negatively correlated with the likelihood of monoculture adoption. In the first case, a likely explanation is that poor households -like those benefiting from social aid- lack the resources to buy food in the market so they must rely on what they produce on their farms. As these kinds of households rely on subsistence agriculture, they must maintain diversified farms to meet their dietary requirements. In the case of monoculture adoption, the negative correlation may reflect that poor farmers lack the resources to engage in commercial agriculture. Similarly, it may indicate that poor farmers need to produce many crops as they are not able to buy food in the markets (Vasco, Tafur, et al., 2021). Beyond these arguments, these findings confirm the importance of diversified agrosystems for food security, food sovereignty and poverty alleviation of rural people in the developing world (Altieri et al., 2012).

Accessibility is another factor that shapes crop richness and monoculture adoption. Households located next to a road have less diverse farms and are more likely to adopt unsustainable production systems. Roads facilitate the transport of agricultural produce to urban markets; therefore, households located next to a road may be encouraged to abandon traditional agriculture in favor of more profitable commercial agriculture (i.e., monoculture). As it is the case of education, the construction of roads in rural areas is seen as a development priority to improve the livelihoods of rural people as it may facilitate the transport of goods and services (Vasco, Tamayo, and Griess, 2017). Nevertheless, such a policy may have negative externalities like increasing deforestation rates (Vasco, Torres, et al., 2017), and -as shown here- encouraging rural people to adopt unsustainable practices.

There are regional differences that are worth noting. Crop richness is smaller in the coast than in the Highlands. A possible explanation for this finding is that, as mentioned earlier in section 2, most of Ecuador's exportable commodities are produced in the coast; therefore, households in that region may exhibit a strong drive for cash crop production (Vasco and Tamayo, 2017) and have, to a great extent, abandoned traditional production systems.

The likelihood of monoculture adoption is higher in the *Sierra* than in the *Amazonia*, which may be associated with still incipient agricultural sector in the Amazon (Sellers et al., 2017) and many native Amazonian people practicing the *chakra* traditional system (Coq-Huelva et al., 2017).

# 6 Conclusions and policy implications

This paper has analyzed the determinants of crop richness and monoculture adoption in Ecuador. Results show that large indigenous households that receive the *Bono de Desarrollo Humano* have higher crop richness in their farms. In contrast, households headed by individuals who have completed university, have off-farm income and are located next to a road, grow fewer crops. In terms of monoculture, the likelihood of adopting such a system is higher for households using pesticides, having off-farm work and residing next to a road. On the other hand, numerous indigenous households receiving the *Bono de Desarrollo Humano* are the least likely to engage in monoculture. Beyond these conclusions, this paper also offers some policy recommendations.

First, our results are in line with prior literature (Altieri et al., 2012; Altieri, 2009; Astier et al., 2017) highlighting the importance of indigenous agriculture for preserving and promoting sustainable agricultural systems. While our findings show that indigenous households do have more diversity of crops in their farms and are more averse to engage in unsustainable practices (i.e., monoculture), previous research addresses that, when in contact with the market economy, indigenous populations also engage in unsustainable practices including monoculture and the use of pesticides (Vasco, Torres, et al., 2021). In this sense, policy makers should focus on rescuing and promoting the (re)adoption of traditional production systems among indigenous peoples.

Second, maintaining a diversified farm seems to demand high amounts of both family and extra-family labor. This is consistent with critics of peasant agriculture holding that it depends on the (over)exploitation of family labor, rather than in farmers' capacity to adapt to changing environments and farmers' technical knowledge (Heynig, 1982). In any case, if the adoption of sustainable systems is a rural development priority, research efforts should be oriented to develop labor saving technologies for traditional production systems.

Third, the results presented here suggest that crop diversity is higher in households receiving social aid from the government. While this suggests that deprived households do not have the resources to buy food on the market and so must produce most of the food they consume, it also reflects that diversified agrosystems are key for food security of poor rural households. In this sense, policies oriented to reduce poverty and hunger in rural areas should focus on promoting traditional and sustainable food systems as a tool to improve food security in rural areas.

# Author's contribution

**C.L.V.P.:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – Original Draft, Writing – Review & Editing. **L.J.C.L.:** Data Curation, Validation, Software, Writing – Review & Editing.

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*Review / Reseña bibliográfica*

Agricultural Sciences



# *In vitro* propagation of banana (*Musa* spp.) by somatic embryogenesis

# Propagación *in vitro* de banano (*Musa* spp.) por embriogénesis somática

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**Abstract**

The banana is a fruit of great consumption worldwide due to its high nutritional value and is a source of economic income for producing countries. However, the susceptibility of cultivars to pests and diseases, and the complexity of plant regeneration due to high levels of ploidy and sterility, hinder the process of plant propagation. Somatic embryogenesis (SE), through embryogenic cells, constitutes an effective tool for the mass propagation of banana plants due to high multiplication coefficients and low production costs. The purpose of this article is to describe the processes of *in vitro* propagation of banana plants (*Musa* spp.) through a bibliographic review of the applications of somatic embryogenesis in micropropagation and genetic improvement. A systematic review was conducted in specialized search engines and databases through three stages: planning, execution, and summary.The most relevant results indicate that SE represents an alternative for plant multiplication due to its enormous potential for tissue regeneration in a short period. However, the risk of somaclonal variation has limited its expansion on a commercial scale. On the other hand, SE is being used in studies related to the genetic transformation of plants. The susceptibility of the crop to diseases such as *M. fijiensis*, *F. oxysporum* f. sp. *cubense* (Foc R4T), and banana streak virus (BSV) has encouraged the development of resistant varieties through embryogenic cell culture and the use of protoplasts. Similarly, the application of gene transfer or gene editing techniques has made it possible to obtain new varieties with resistance or tolerance to the main crop diseases.

***Keywords***: *Callus*, Genetic variability, *In vitro*, *Musa*, Somatic embryogenesis.

**Resumen**

El banano es una fruta de gran consumo a nivel mundial por su alto valor nutritivo y es fuente de ingresos económicos para los países que se dedican a la producción de la fruta. Sin embargo, la susceptibilidad de los cultivares a plagas y enfermedades evidencia la baja producción en el cultivo. Asimismo, los altos niveles de ploidía y esterilidad dificultan el proceso de propagación de plantas. La embriogénesis somática (ES), a través de células embriogénicas, constituye una herramienta eficaz para la propagación masiva de plantas de banano por los altos coeficientes de multiplicación y bajos costos de producción. El presente artículo tiene como finalidad describir los procesos de propagación *in vitro* de plantas de banano (*Musa* spp.), mediante una revisión bibliográfica de las aplicaciones de embriogénesis somática en la micropropagación y mejoramiento genético. Para lo cual se realizó una revisión sistemática en buscadores especializados y bases de datos, a través de tres etapas: planificación, ejecución y resumen. Los resultados más relevantes indican que la ES representa una alternativa para la multiplicación de plantas, por el gran potencial para la regeneración de tejidos en un corto periodo de tiempo. Sin embargo, el riesgo de variación somaclonal ha limitado su expansión a escala comercial. Por otro lado, la ES está siendo empleada en estudios relacionados con la transformación genética de plantas. La susceptibilidad del cultivo a enfermedades como *M. fijiensis*, *F. oxysporum* f. sp. *cubense* (Foc R4T) y virus rayado del banano (BSV), ha incentivado el desarrollo de especies resistentes a través del cultivo de células embriogénicas y uso de protoplastos. De igual forma, la aplicación de técnicas de transferencia de genes o edición genética ha permitido obtener nuevas especies con resistencia o tolerancia a las principales enfermedades del cultivo.



***Palabras clave***: *Callos*, Embriogénesis somática, *In vitro*, *Musa*, Variabilidad genética.

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# 1 Introduction

Banana plants produce fruits that are highly valued in tropical and subtropical regions worldwide (Tran et al., 2016). Bananas rank second among fruit crops, with a production of 115.7 million tons, and constitute one of the crops with the greatest impact on the economies of exporting countries (FAO, 2020). However, classical propagation methods of edible *Musa* spp. are complex due to levels of ploidy and sterility (Simoníková et al., 2022). Somatic embryogenesis (SE) is a tool for the mass propagation of high-yielding genotypes (Tran et al., 2016). This technique consists of selecting zygotic embryos, proliferating meristems or scalps, as well as male and female flowers (Ahmed et al., 2014). The selected material initiates a process of embryogenic callus induction, followed by the establishment of embryogenic cell suspensions, the formation of somatic embryos, maturation, and germination; subsequently, plants enter the acclimatization process before being transferred to open field conditions (Escobedo-Gracia et al., 2016; Taco et al., 2026).

Despite the high plant regeneration capacity, this specialized technique is mainly directed toward genetic improvement rather than commercial propagation, due to the risk of somaclonal variation, in comparison with plants obtained through organogenesis (Galán et al., 2018). Somatic cell suspension cultures constitute an alternative for banana plant improvement (Liu et al., 2017). However, the use of protoplasts obtained through embryogenesis from cell suspension cultures (ECS) has been frequently employed because of their high yield, high activity, ease of operation, and wide adaptability (Wu et al., 2020). Current genetic transformation methods include *Agrobacterium*-mediated transformation (Kovács et al., 2013), particle bombardment (Vishnevetsky et al., 2011), and CRISPR/Cas9 (Wu et al., 2020).

These approaches have enabled genetic improvements in cultivars susceptible to diseases (Shivani et al., 2017), such as the development of plants resistant to banana streak virus (BSV) and *Mycosphaerella fijiensis* (Tripathi et al., 2019; Kovács et al., 2013). Despite the development of improved banana plants and the achievement of ideal plant architecture, sustained immune responses are consistently accompanied by yield reductions (Wang et al., 2021). Therefore, it is necessary to conduct studies on the *Musa* spp. genome, perform gene-editing experiments, and establish *in vitro* culture protocols that allow optimization of banana plant transformation processes. Consequently, this review article aims to describe the *in vitro* propagation processes of banana plants (*Musa* spp.) through a bibliographic review of the applications of somatic embryogenesis in micropropagation and genetic improvement.

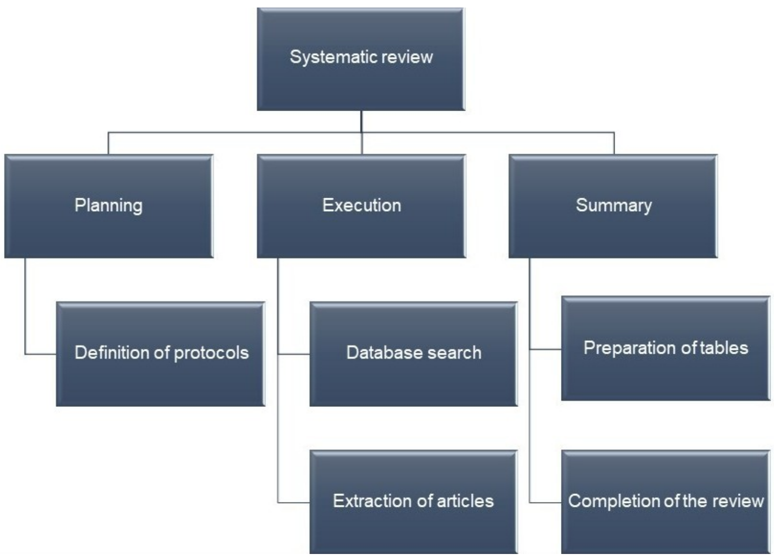


**Figure 1.** Methodological process of critical screening of scientific articles.

## 2 Methodology

The systematic review was conducted through three stages (Moreno et al., 2018): planning, execution, and synthesis (Figure 1). The selected information corresponds to articles published over the last 10 years, with some exceptions included due to their relevance to the literature review.

During the planning stage, a protocol was developed to be followed throughout the entire review process. This protocol included information such as article title, authors, objective, keywords, research sources, inclusion and exclusion criteria, and type of study. In the execution stage, bibliographic information was obtained from specialized databases such as ResearchGate, Semantic Scholar, Google Scholar, Springer, SciELO, ScienceDirect, Frontiers, and PubMed. Automated searches were conducted based on titles, keywords, and abstracts (Figure 2). The synthesis stage comprised the preparation of figures and tables, as well as the writing of the manuscript.

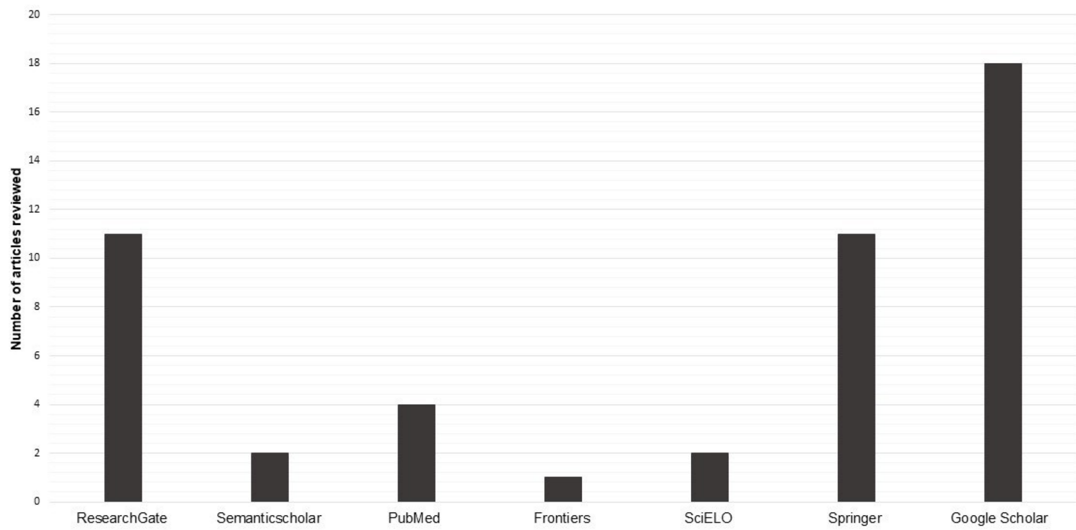


**Figure 2.** Systematic review in specialized search engines.

## 3 *In vitro* culture in banana

Banana is a monocotyledon belonging to the genus *Musa* spp. and is among the most important and widely distributed crops in humid tropical and subtropical regions worldwide (Escobedo-Gracia et al., 2016). In Ecuador, banana cultivation represents the most economically relevant agricultural activity (Capa Benítez et al., 2016). In addition, the country is the world's leading exporter, supplying markets such as the European Union, the United States, Asia, among others (MAGAP, 2016). Currently, diploid and triploid hybrids originating from natural intraspecific crosses (2n = 2x = 22 chromosomes) are cultivated, derived from *Musa acuminata* Colla (genome A) and *Musa balbisiana* Colla (genome B) (Martin et al., 2020). However, one of the main limitations of banana cultivation is polyploidy and vegetative parthenocarpy (Escobedo-Gracia et al., 2016). Vegetative propagation through natural shoots known as suckers or buds from the rhizome fails to meet the demand for elite genotypes required for crop establishment (Lohidas and Sujin, 2015).

*In vitro* propagation involves excising a small fragment of the plant, known as an explant, and culturing it under aseptic conditions with macronutrients, micronutrients, carbohydrates, vitamins, growth regulators, and occasionally amino acids, all developed under controlled environments (Ahmed et al., 2014). This technique comprises four stages:

establishment, multiplication, rooting, acclimatization, and hardening (Rodríguez, 2013).

In banana, *in vitro* propagation is carried out using apical meristems extracted from the rhizome, as these exhibit longitudinal growth as a result of cellular totipotency (Ahmed et al., 2014). To ensure normal development, meristems must be established in an optimal culture medium composed of inorganic salts, organic compounds, complex natural preparations, and inert support materials (Anbazhagan et al., 2014). The most widely used culture medium for *in vitro* propagation of banana and plantain is that proposed by Murashige and Skoog (MS). The basal composition of salts and minerals in the MS formulation allows the explant to adapt to micropropagation processes, although many laboratories incorporate specific modifications based on the nutritional requirements of each plant (Galán et al., 2018). Other alternatives include the Gamborg (B5), Schenk and Hildebrandt (SH), and Linsmaier and Skoog (LS) media (Ngomuo et al., 2014). Therefore, the use of a culture medium with an appropriate composition is essential to ensure *in vitro* growth and development of each cultivar.

Plant regeneration can be achieved through organogenesis and somatic embryogenesis (Galán et al., 2018). The former is characterized by the formation of a unipolar primordium from a bud, giving rise to the development of a vegetative shoot that maintains a direct relationship with the maternal tissue. This technology is simple and well known and can be performed using buds, apices, or meristems; it has been widely used in systematic processes for commercial propagation. Somatic embryogenesis (SE), by contrast, consists of the formation of an embryo from a single cell or a group of cells. Somatic embryos do not have a vascular connection with the maternal tissue, as they are not products of gamete fusion; however, they must have the capacity to grow and form the entire plant structure. This method is considered the most efficient for *in vitro* plant propagation due to high multiplication rates in short periods of time and the ease of automating production processes (Morais-Lino et al., 2016). Nevertheless, its application in banana and plantain propagation is somewhat limited due to somaclonal variation and the scarcity of field studies on plants obtained through these processes.

## 4 Somatic embryogenesis

Somatic embryogenesis is a process that consists of embryo formation from a cell without the need for gamete fusion (Quiala et al., 2021). Cells undergo specific morphological and biochemical processes that lead to the formation of a somatic embryo (Shivani et al., 2017). Somatic embryos constitute new individuals and are characterized by a bipolar structure with apical and radical meristems, enabling them to develop into a complete plant (Horstman et al., 2017). SE represents a model of cellular totipotency involving signaling networks and reprogramming of gene expression patterns that are specifically regulated by plant growth regulators or environmental conditions (Nic-Can and Loyola-Vargas, 2016). It can occur via two pathways: direct and indirect (Grzyb et al., 2018). In direct SE, embryos at advanced developmental stages exhibit low uniformity and this approach is commonly used for plant regeneration. In contrast, indirect SE produces numerous somatic embryos at early stages with uniform development and is used to establish cell suspension cultures (Shivani et al., 2017). In monocotyledons, somatic embryo development progresses through globular, scutellar, and coleoptilar stages (Yuan et al., 2016).

The production of plants through SE consists of five phases: embryo induction, proliferation, maturation, germination, and plant conservation (Bradaï and Sánchez-Romero, 2021). Embryo induction begins with the formation of proembryogenic masses in culture media containing auxins to promote cellular aggregation. Subsequently, tissues are transferred to auxin-free media to stimulate cell division and embryo formation. Embryogenic tissues proliferate, leading to cell expansion and reserve accumulation; roots and shoots develop under *in vitro* conditions, and finally explants are transferred *ex vitro* for acclimatization and complete plant development (Quiala et al., 2021).

It is important to consider that donor tissues, culture media, and growth conditions influence plant regeneration via SE (Pencik et al., 2015). Therefore, understanding the physiological and molecular mechanisms involved in SE induction is essential (Méndez-Hernández et al., 2019). The addition of growth regulators in different proportions helps break dormancy and improves shoot formation (Márquez-López et al., 2018). Cytokinins are responsible for shoot formation and bud growth, whereas auxins are involved in root formation. SE employs biotechnological tools with the potential for genetic improvement and mass plant production (Zhou et al., 2016). Additionally, this technique is used in studies of cellular differentiation, gene expression, and molecular genetics. Embryogenic cell suspension cultures accelerate mass banana propagation due to their high regenerative potential and constitute an important non-conventional tool for plant improvement (Escobedo-Gracia et al., 2016).

## 5 Initiation of somatic embryogenesis in banana

The initiation of somatic embryogenesis is influenced by the selected plant material (Morais-Lino et al., 2016) and the balance of growth regulators in the culture medium (Tran et al., 2016). Uma et al. (2021) and Morais-Lino et al. (2016) report that the plant material used for SE in banana cultivation consists of male inflorescences, which should be collected during the tenth week after emergence (Natarajan et al., 2018) (Figure 3).

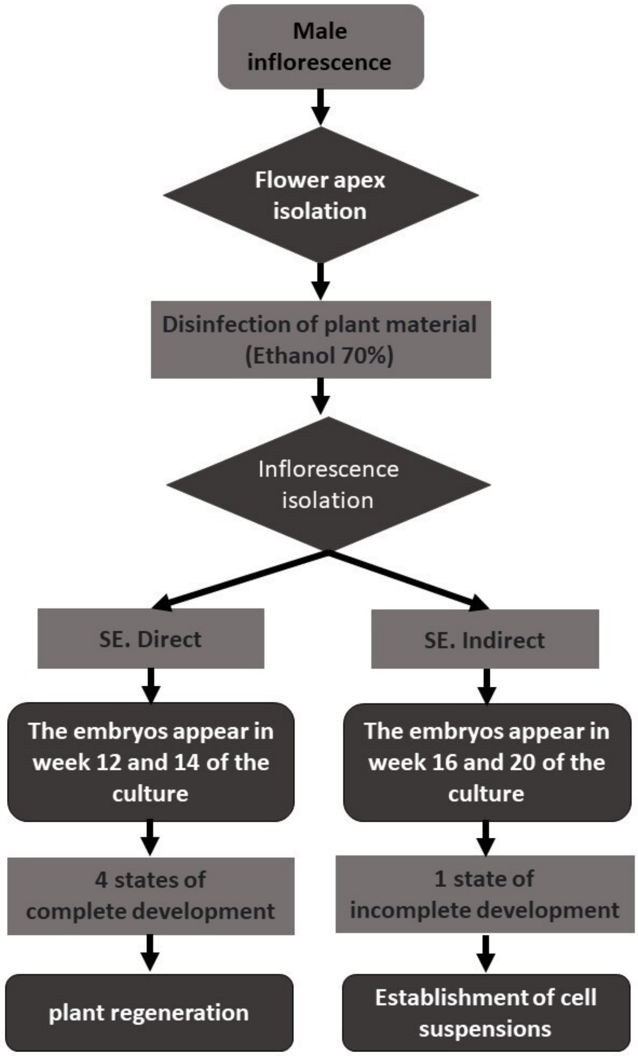


**Figure 3.** Process of somatic embryogenesis induction in banana.

Immature floral apices are sectioned layer by layer in a two-step process (Shivani et al., 2017). To remove bracts and prevent contamination by external agents, the material must be disinfected with 70% (v/v) ethanol to reduce exogenous contamination of plant tissues (Natarajan et al., 2018). Another key factor is the position of the hands obtained from the inflorescence; selection of the sixth to eighth hands allowed the formation of 50.0 ± 0.54% callus in 'Grand Naine' and 48.0 ± 1.67% in 'Rasthal'. According to Natarajan et al. (2018), this aspect influences embryogenic callus induction.

Floral apices are inoculated in MS medium containing salts, vitamins, 3% sucrose, and exogenous auxin-type growth regulators to induce the formation of cellular aggregates (Shivani et al., 2017). Morais-Lino et al. (2016) reported that growth regulator concentrations of 1 mg/L IAA + 4 mg/L 2,4-D + 1 mg/L NAA supplemented with glutamine induce callus formation in 50% of explants (Uma et al., 2021). In contrast, Youssef et al. (2010) reported that MS medium supplemented with 5.71 $\mu$M IAA, 18 $\mu$M 2,4-D, 5.4 $\mu$M NAA, 4.1 $\mu$M biotin, and 87 mM sucrose resulted in 81% callus formation in 'Williams' bud explants and 52.11% in 'Grand Naine' bud explants. Therefore, growth regulators enable the formation of embryogenic calli when applied at optimal concentrations according to cultivar and species. To induce SE, environmental factors must also be considered; thus, culture media containing plant material should be incubated at 27 °C under dark conditions for 12 days (Shivani et al., 2017) (Table 1).

**Table 1.** Composition of culture media for the initiation of indirect somatic embryogenesis in *Musa* spp.

| **Components** | **Male flowers** | **Male flowers** | **Meristems** | **Male flowers** | **Male flowers** |
|---|---|---|---|---|---|
| Macroelements | MS | MS | MS | MS | MS |
| Microelements | MS | MS | MS | MS | MS |
| Vitamins | MS | MS | MS | MS | MS |
| Biotin | 1 mg $L^{-1}$ | 4,1 $\mu$M | – | – | – |
| Malt extract | 100 mg $L^{-1}$ | – | – | – | – |
| NAA | 1 mg $L^{-1}$ | 5,4 $\mu$M | – | 1 mg $L^{-1}$ | 1 mg $L^{-1}$ |
| IAA | 1 mg $L^{-1}$ | 5,71 $\mu$M | – | 1 mg $L^{-1}$ | 1 mg $L^{-1}$ |
| 2,4-D | 4 mg $L^{-1}$ | 18 $\mu$M | – | 4 mg $L^{-1}$ | 4 mg $L^{-1}$ |
| Picloram | – | – | – | – | – |
| 6-BA | – | – | 13,31 $\mu$M | – | – |
| L-Glutamine | 100 mg $L^{-1}$ | – | – | – | 50 mg $L^{-1}$ |
| Sucrose | 30 g $L^{-1}$ | 87 mM | 30 g $L^{-1}$ | 3% | 3% |
| Phytagel | 2,6 g $L^{-1}$ | – | – | – | – |
| Agar | – | – | 7 g $L^{-1}$ | 0,70% | 0,70% |
| Gelrite | – | 2 g $L^{-1}$ | – | – | – |
| pH | 5,8 | 5,7 | 5,7 | 5,8 | 5,8 |
| **References** | (S. Khalil et al., 2002) | (Youssef et al., 2010) | (Remakanthan et al., 2014) | (Morais-Lino et al., 2016) | (Morais-Lino et al., 2016) |

## 6 Proliferation and initiation of embryogenic callus from cell suspension cultures

After the incubation period (4–6 months), the appearance of different types of calli begins. These are evaluated monthly during the first three months, followed by periodic evaluations every 15 days. After four months of culture, an embryogenic callus of friable nature develops, composed of whitish–translucent proembryogenic masses. Due to its characteristics, this callus is considered ideal for the establishment of cell suspension cultures (Morais-Lino et al., 2016).

Once the ideal calli have been identified, the establishment of embryogenic cell suspension cultures is initiated. According to Shivani et al. (2017), 24-week-old embryogenic calli are cultured in MS medium supplemented with 2,4-D, incubated at 27 °C in darkness, under constant agitation at 90 rpm, with subcultures performed every 7 days. In contrast, Strosse et al. (2003) report that calli should be transferred to a liquid MS medium supplemented with 1 mg/L IAA, 1.1 mg/L 2,4-D, and 250 $\mu$g/L zeatin, with the pH adjusted to 5.8, to promote the multiplication of embryogenic cells.

**Table 2.** Composition of culture media for the induction and proliferation of embryogenic calli

| **Components** | **cv. Dwarf Brazilian** | **M.a. cv. Grand Colla (AAA)** | **M.a. cv. Grand Naine (AAA)** | **M.a. cv. Grand Naine (AAA)** |
|---|---|---|---|---|
| Macroelements | MS | MS 1/2 | MS | MS |
| Microelements | MS | MS 1/2 | MS | MS |
| Biotin ($\mu$M) | 1 mg $L^{-1}$ | – | – | – |
| Malt extract | 100 mg $L^{-1}$ | – | – | – |
| NAA | 1 mg $L^{-1}$ | – | – | – |
| IAA | 1 mg $L^{-1}$ | – | – | – |
| 2,4-D | 4 mg $L^{-1}$ | 4.5 $\mu$M | – | 0.90 $\mu$M |
| Picloram | – | – | 4.14 $\mu$M | – |
| 6-BA | – | – | 0.22 $\mu$M | – |
| L-Glutamine | 100 mg $L^{-1}$ | – | – | – |
| Sucrose | 30 g $L^{-1}$ | 174 mM | 30 g $L^{-1}$ | 30 g $L^{-1}$ |
| Casein | 200 mg $L^{-1}$ | – | – | – |
| Proline | 2 mg $L^{-1}$ | – | – | – |
| Gelrite | – | 2 g $L^{-1}$ | – | – |
| Agar | – | – | 7 g $L^{-1}$ | 7 g $L^{-1}$ |
| $KH_2PO_4$ | – | 200 mg $L^{-1}$ | – | – |
| pH | 5.8 | 5.8 | 5.7 | 5.7 |
| **References** | (S. Khalil et al., 2002) | (Youssef et al., 2010) | (Remakanthan et al., 2014) | (Remakanthan et al., 2014) |

Alternatively, Morais-Lino et al. (2016) indicate that embryogenic masses are transferred to a liquid MS medium supplemented with 1 mg/L 2,4-D, 100 mg/L glutamine, 1 mg/L biotin, 10 mg/L ascorbic acid, and 44.5 g/L sucrose, under dark conditions at 27 ± 2 °C, with constant agitation at 120 rpm and subcultures every 10 days. At each subculture, the suspensions are filtered through a sieve to remove contaminated cells or cells that do not meet the characteristics required for the establishment of somatic embryogenesis from callus-derived embryogenic cell suspensions (ECS) (Morais-Lino et al., 2016).

One of the main problems in callus induction is the exudation of phenolic compounds into the culture medium, which are inherent to the nature of Musaceae and induce browning, decomposition, and hyperhydricity of the calli. An effective alternative to reduce phenolization levels is the use of antioxidants such as melatonin (50 mg $L^{-1}$) and L-glutamine (100 mg $L^{-1}$) in the callus induction medium (Natarajan et al., 2018).

Analysis of gene expression in embryogenic calli treated with 2,4-dichlorophenoxyacetic acid indicated that this growth regulator acts as an inducer of gene expression (*MaBBM1*, *MaBBM2*, *MaWUS2*, and *MaVP1*) (Shivani et al., 2017). This expression may be key to banana plant regeneration.

## 7 Development and maturation of the somatic embryo

Once the embryogenic callus has been formed (3–5 months) in a specific culture medium (Escobedo-Gracia et al., 2016), the next step is the proliferation of embryogenic tissue. This process is carried out in MS medium containing salts and vitamins, supplemented with 87 mM sucrose, 4.52 $\mu$M 2,4-D, 4.1 $\mu$M biotin, 680 $\mu$M glutamine, 100 mg $L^{-1}$ malt extract, with the pH adjusted to 5.3, under constant agitation at 90 rpm and 27 °C in darkness. The medium must be renewed weekly, and the cell suspensions should be adjusted to a defined volume (Enríquez, 2019).

To determine SE growth and define the correct subculture times, it is necessary to establish the growth curve of the cell suspension. To do this, 1.5 ml of somatic cells are taken, the initial cell concentration is determined, and 50 ml of MS liquid medium is added. Growth is calculated by the change in cell volume for the evaluation interval every 5 days for 40 days. Likewise, the quality of embryogenic cell suspensions is determined by evaluating cell constitution (cell types), coloration, multiplication rate, and regeneration power (Morais-Lino et al., 2016).

**Table 3.** Comparison of the composition of culture media used for the initiation and maintenance of embryogenic cell suspension cultures

| **Components** | **M.a. cv. Grand Naine (AAA)** | **M.a. cv. Grand Colla (AAA)** | **M. a. Colla (AA) ssp. Malaccensis** | **M.a. cv. Grand Naine (AAAAB) Tropical** |
|---|---|---|---|---|
| Macroelements | MS | MS | MS | MS |
| Microelements | MS | MS | MS | MS |
| Vitamins | MS | MS | MS | MS |
| Biotin | 4,1 $\mu$M | – | 4,1 $\mu$M | 1 $mg\,L^{-1}$ |
| 2,4-D | 4,5 $\mu$M | – | 4,5 $\mu$M | 1 $mg\,L^{-1}$ |
| Picloram | – | – | 2,1 $\mu$M | – |
| L-Glutamine | 684 $\mu$M | – | 684 $\mu$M | 100 $mg\,L^{-1}$ |
| Malt extract | 100 $mg\,L^{-1}$ | – | 100 $mg\,L^{-1}$ | 1 $mg\,L^{-1}$ |
| Sucrose | 131 mM | 87 mM | 87 mM | 44.5 $g\,L^{-1}$ |
| Agar | – | – | – | – |
| pH | 5,3 | 5,8 | 5,3 | 5,8 |
| **References** | (Grapin et al., 2000) | (Youssef et al., 2010) | (Escobedo-Gracia et al., 2016) | (Morais-Lino et al., 2016) |

## 8 Plants derived from somatic embryogenesis

The production of plants through the germination of somatic embryos with normal roots and shoots is achieved in substrates containing growth regulators (Escobedo-Gracia et al., 2014). Plant development depends on the genotype and on the procedures applied prior to and during embryo development (Morais-Lino et al., 2016). After the acclimatization and hardening process, conversion rates can be estimated, which are comparable to embryonic germination percentages. These percentages vary according to genotype, ranging from 3% to 46% in triploid Cavendish bananas (AAA); however, when somatic embryos are obtained from embryogenic cell suspension cultures, germination rates can reach up to 91% (Domergue et al., 2000). The highest rates were observed in triploid cv. Dwarf Brazilian (AAB) and *Musa acuminata* cv. Grand Naine (AAA), which share the characteristic that embryo development passes through a differentiation–maturation phase (Remakanthan et al., 2014). Somatic embryos obtained through somatic embryogenesis (SE) from shoot tips, as in the case of *Musa acuminata* AAA cv. Grand Naine, exhibit embryo conversion rates ranging from 2% to 3% (Remakanthan et al., 2014). Some SE protocols described for various banana genotypes report different percentages of somatic embryo germination and embryo conversion rates, since the data presented do not always clearly distinguish between these two processes (Escobedo-Gracia et al., 2016).

Conversion rates range from 13% in edible diploids (AA), from 13% to 25% in Grand Naine of the Cavendish subgroup (AAA), 66.7% in African Highland plantain (AAA) (Namanya et al., 2004), and up to 100% in wild *Musa acuminata* ssp. (AA) (Escobedo-Gracia et al., 2016). Regarding non-conventional improvement approaches (genetic transformation) aimed at counteracting pest problems and achieving higher germination rates, SE processes are essential components of *in vitro* regeneration systems, as they enable the development of resistant varieties (Ghag et al., 2014). For this reason, it is important to continue the ongoing development and optimization of SE protocols for the different cultivated clones (Escobedo-Gracia et al., 2016).

**Table 4.** Comparison of the composition of culture media used for the development and maturation of somatic embryos of *Musa* spp.

| **Components** | **cv. Dwarf Brazilian (AAB)** | ***M. a.* ssp. Malaccensis (AA)** | **cv. Grand Naine (AAA)** | ***M.a.* cv. Grand Naine (AAA)** |
|---|---|---|---|---|
| Macroelements | MS | MS | MS | MS |
| Microelements | MS | MS | MS | MS |
| Vitamins | MS | MW | MS | MS |
| $KH_2PO_4$ (mM) | – | 1.47 mM | – | – |
| Biotin | 4.1 $\mu$M | – | – | – |
| Sucrose | 131 mM | 87.6 mM | 30 $g\,L^{-1}$ | 30 $g\,L^{-1}$ |
| BAP | – | – | 2.2 $\mu$M | 0.8 $mg\,L^{-1}$ |
| NAA | 5.4 $\mu$M | – | 2.68 $\mu$M | – |
| Kinetin | 2.3 $\mu$M | – | – | – |
| Zeatin | 0.9 $\mu$M | – | – | – |
| Malt extract | 100 $mg\,L^{-1}$ | – | – | – |
| Glutamine | 680 $\mu$M | – | – | – |
| Picloram | – | – | – | – |
| IAA | – | – | – | 0.7 $mg\,L^{-1}$ |
| Agar | – | – | – | 7 $g\,L^{-1}$ |
| Phytagel | 2.6 $g\,L^{-1}$ | – | 4 $g\,L^{-1}$ | – |
| Gelrite | – | 2 $g\,L^{-1}$ | – | – |
| pH | 5.8 | 5.8 | 5.7 | 5.8 |
| **References** | (S. M. Khalil and Elbanna, 2004) | (Escobedo-Gracia et al., 2016) | (Remakanthan et al., 2014) | (Morais-Lino et al., 2016) |

**Table 5.** Culture medium composition commonly used for the germination of somatic embryos in *Musa* spp.

| **Components** | **cv. Grand Naine (AAA)** | ***M.a.* cv. Grand Colla (AAA)** | ***M.a.* cv. Grand Naine (AAA)** | ***M.a.* cv. Grand Naine (AAA)** | **Tropical (AAAAB)** |
|---|---|---|---|---|---|
| Macroelements | MS | MS | MS | MS | MS |
| Microelements | MS | MS | MS | MS | MS |
| Vitamins | MS | MS | MS | MS | MS |
| $KH_2PO_4$ (mM) | 1,47 mM | – | – | – | – |
| Sucrose | – | 87 mM | – | 30 $g\,L^{-1}$ | 30 $g\,L^{-1}$ |
| BAP | – | 0,22 $\mu$M | 0,22 $\mu$M | 0,8 $mg\,L^{-1}$ | 0,2 $mg\,L^{-1}$ |
| Picloram | – | – | 4,14 $\mu$M | – | – |
| IAA | 1,14 $\mu$M | 1,14 $\mu$M | – | 0,7 $mg\,L^{-1}$ | 0,1 $mg\,L^{-1}$ |
| Agar | – | – | – | 7 $g\,L^{-1}$ | 7 $g\,L^{-1}$ |
| Gelrite | – | 2 $g\,L^{-1}$ | – | – | – |
| pH | – | 5,8 | – | – | – |
| Number of embryos | – | – | 355,83±31,72 | 6076,6 | 106,0 |
| % Germination | 35–46 | 35 | 100 | – | – |
| % Conversion | – | – | – | 20,21 | 79,72 |
| **References** | (S. M. Khalil and Elbanna, 2004) | (Youssef et al., 2010) | (Remakanthan et al., 2014) | (Morais-Lino et al., 2016) | (Morais-Lino et al., 2016) |

**Table 6.** Biotechnological companies with phytosanitary certification to import *in vitro* banana plants (*Musa sapientum*) into Ecuador.

| Company | Country of origin | Phytosanitary Certificate<br>Plants free of: |
|---|---|---|
| Agribiotecnología<br>Cristal Vitro | Costa Rica | Banana bunchy top virus (BBTV)<br>Banana streak badnavirus (BSV)<br>Banana bract mosaic potyvirus (BBMV)<br>Banana bract mosaic virus (BBrMV)<br>Abaca mosaic virus (ABTV)<br>Abaca mosaic virus (AbaMV)<br>Banana mild mosaic virus (BanMMV)<br>Banana virus X (BVX)<br>*Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 |
| Genética Salvadoreña S.A. | El Salvador | Cucumber mosaic virus (CMV)<br>Abaca mosaic virus (ABTV)<br>Banana bunchy top virus (BBTV)<br>Banana streak badnavirus (BSV)<br>Banana bract mosaic virus (BBMV)<br>Banana mild mosaic virus (BanMMV)<br>Banana virus X (BVX) y<br>*Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 |
| Galiltec S.A. | Honduras | Banana streak virus (BSV)<br>Banana bunchy top virus (BBTV)<br>Banana bract mosaic potyvirus (BBMV)<br>Banana bract mosaic virus (BBrMV)<br>Abaca mosaic virus (ABTV)<br>Abaca mosaic virus (AbaMV)<br>Banana mild mosaic virus (BanMMV)<br>Banana virus X (BVX)<br>*Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 |
| Rahan Meristem del Ecuador Cía. Ltda | Israel | Banana bunchy top virus (BBTV),<br>Cucumber mosaic virus (CMV)<br>Banana streak badnavirus (BSV),<br>Banana bract mosaic virus (BBrMV)<br>Abaca bunchy top virus (ABTV)<br>Abaca mosaic virus (AbaMV)<br>Banana mild mosaic virus (BanMMV)<br>Banana virus X (BVX)<br>*Fusarium oxysporum* f. sp. *cubense* Raza 4 Tropical |
| Nature Source Improves Plants de México, S.A. | México | Banana bunchy top virus (BBTV)<br>Banana streak badnavirus (BSV)<br>Banana bract mosaic potyvirus (BBMV)<br>Banana bract mosaic virus (BBrMV)<br>Abaca mosaic virus (ABTV)<br>Abaca mosaic virus (AbaMV)<br>Banana mild mosaic virus (BanMMV)<br>Banana virus X (BVX)<br>*Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 |
| Du Roi | Sudáfrica | Banana bunchy top virus (BBTV)<br>Banana rayado badnavirus (BSV)<br>Banana bract mosaic potyvirus (BBMV)<br>Banana bract mosaic virus (BBrMV)<br>Abaca mosaic virus (ABTV)<br>Abaca mosaic virus (AbaMV)<br>Banana mild mosaic virus (BanMMV)<br>*Fusarium oxysporum* f. sp. *cubense* Raza 4 Tropical |

**Source:** Agrocalidad, (2022)

**Table 7.** Registered establishments for the *in vitro* propagation of banana plant material (*Musa sapientum*).

| Legal Name | Canton | Status | Type of Operation | Type/Area |
|---|---|---|---|---|
| BIOFABRICA MONTUBIA S.A.S. | Machala | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| SEBIOCA C.A. EN LIQUIDACIÓN | Guayaquil | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| RAHAN MERISTEM DEL ECUADOR CIA. LTDA. | Guayaquil | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| VITROLIFE S.A. | Guayaquil | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| ONE VITRO S.A. | Durán | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| BIOGENETICAGREEN C.A. | Quito | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| GERMOPLANTA CIA. LTDA. | Rumiñahui | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| ORANGELAB S.A. | Quito | Registered | Meristematic micropropagator | Micropropagation Laboratory |
| YURA BUSINESS S.A.S. | Quito | Registered | Meristematic micropropagator | Micropropagation Laboratory |

**Source:** Agrocalidad, (2022)

## 9 Somaclonal variation in plants regenerated through somatic embryogenesis

A feature of *in vitro* plant tissue cultures is the occurrence of somaclonal variation, involving genetic changes in cultured cells and tissues (Nwauzoma and Jaja, 2013). In some cases, this variation is exploited for genetic improvement, allowing the expansion of natural genetic variability (Wang et al., 2021); however, when clonal propagation is intended, somaclonal variation represents an undesirable anomaly.

The *in vitro* culture environment, including the type and concentration of plant growth regulators, together with the genetic background of the explant, as well as the total number and duration of subcultures, can alter the characteristics of plants regenerated from somatic embryos. All these factors contribute to the generation of genetic and epigenetic variation (Escobedo-Gracia et al., 2014), which is expressed at the phenotypic level and is known as somaclonal variation (Youssef et al., 2010). This variation may constitute pre-existing genetic variation in the explant due to changes in chromosome number or variation induced by *in vitro* culture conditions; additionally, DNA mutations and epigenetic changes at the sequence level may also occur (Wang et al., 2021).

It is also known that somaclonal variation in banana cultivation is associated with long-term cultures or cultures that involve a callus phase or high rates of multiplication treatments (Nwauzoma and Jaja, 2013). On the other hand, the reduction in the regeneration capacity of cultures derived from embryogenic cell suspensions is associated with cytogenetic instability in triploid bananas (AAA genome) of the Cavendish subgroup, off-type regenerants from long-term cell suspension cultures, and the subsequent loss of regeneration potential (Wu et al., 2020).

The regeneration process via somatic embryogenesis showed greater genetic stability compared with plantlets regenerated from long-term cultures, in which a higher DNA content was detected (Escobedo-Gracia et al., 2016). Regarding genetic instability/stability, when evaluating morphological and agronomic parameters, variation ranges from approximately 0.3% to 3.6%; meanwhile, molecular markers recorded low variation levels between 1.4% and 1.6%, within the natural variation found in the mother plant used as the explant source (Ghag et al., 2014).

**Table 8.** Somaclonal variation in banana plants regenerated through *in vitro* somatic embryogenesis.

| **Plant material** (genome composition) | **Tissue /source of variation** | **Detection method** | **Percentage of variation (%)** | **References** |
|---|---|---|---|---|
| *M. a.* (AAA) cv. Grand Naine | Embryogenic culture | AFLP | 1.4 | Youssef et al. (2010) |
| *M. a.* (AAA) cv. Williams | Embryogenic culture | AFLP | 1.6 | Youssef et al. (2010) |
| Grand Naine (AAA) | Cell suspensions | SSR primers | 0 | Morais-Lino et al. (2016) |
| Tropical (AAAB) | Cell suspensions | SSR primers | 0 | Morais-Lino et al. (2016) |
| cv. Valery (AAA) | Embryogenic culture | Chromosome counting | 30 % aneuploidy | Moradi et al. (2017) |

**Table 9.** Results of banana genetic improvement through *in vitro* plant generation processes.

| **Cultivar** | **Tissue / origin** | **Expressed gene / target gene** | **Gene transfer technique** | **Modified trait** | **Transgenic plant** | **References** |
|---|---|---|---|---|---|---|
| Grand Nain (AAA) | ECS (male flowers) | Endochitinase gene *ThEn-42* from *Trichoderma* cwith grape stilbene synthase gene (StSy) and tomato (Cu, Zn-SOD) superoxide dismutase gene | Biolistics | Resistance to *M. fijiensis* | Yes | Vishnevetsky et al. (2011) |
| Gros Michel (AAA) | ECS (male flowers) | Rice chitinase genes | *Agrobacterium* | Resistance to *M. fijiensis* | Yes | Kovács et al. (2013) |
| *Musa acuminata* L. AA, cv. Mas | Male flowers – direct organogenesis | GUS | Ballistics + *Agrobacterium* | – | Yes | Liu et al. (2017) |
| Cavendish “Williams” | ECS (male flowers) | gRNA | CRISPR/ Cas9 | Disease resistance | Yes | Naim et al. (2018) |
| “Gonja manjaya” (AAB) | *in vitro* plants | gRNA1 (ORF1), gRNA2 (ORF2), gRNA3 (ORF3) | CRISPR/ Cas9 | Resistance to banana streak virus (BSV) | Yes | Tripathi et al. (2019) |
| Cavendish (AAA) | Protoplasts | sgRNA | CRISPR/ Cas9 | Disease resistance | Yes | Wu et al. (2020) |

*Note:* ECS = Embryogenic Cell Suspension .

## 10 Genetic transformation of banana using somatic embryogenesis cultures

The development of improved banana varieties through conventional methods represents a challenge due to low genetic variability, polyploidy, and sterility of commercial cultivars (Tripathi et al., 2019). Therefore, somatic embryogenesis constitutes an alternative technique for banana plant improvement (Liu et al., 2017). Likewise, the use of protoplasts obtained through embryogenesis from embryogenic cell suspension cultures (ECS) is favored because of their high yield, high activity, ease of operation, and broad adaptability (Wu et al., 2020). Genetic transformation methods used in banana include *Agrobacterium*-mediated transformation (Kovács et al., 2013), particle bombardment (Vishnevetsky et al., 2011), and CRISPR/Cas9 (Wu et al., 2020).

Genome-editing technologies are valuable tools for exploring the underlying mechanisms of gene function and regulation and can serve as a platform for crop genetic improvement through the removal of undesirable chromosomal DNA, positive or negative regulation of endogenous genes, and the introduction of novel coding sequences (Liu et al., 2017). Table 9 describes the main results obtained in banana plant regeneration.

## 11 Conclusions

Banana propagation through somatic embryogenesis represents an alternative for plant multiplication due to its high potential for tissue regeneration within a short period of time. However, the risk of somaclonal variation that explants may exhibit has limited its expansion at the commercial scale. Therefore, it is necessary to develop specific protocols for each species, select appropriate plant material, and identify the type of genotype to ensure the success of plant micropropagation. On the other hand, the genetic variability exhibited by explants subjected to this technique has been used in studies related to the genetic transformation of banana plants.

The susceptibility of the crop to diseases such as *M. fijiensis*, *Fusarium oxysporum* f. sp. *cubense* (Foc TR4), and banana streak virus (BSV) has encouraged the development of new *in vitro* establishment protocols for resistant species. Large-scale propagation of plants through embryogenesis is an effective alternative for banana monocultures during each renewal cycle; therefore, process traceability is necessary to identify mutations. The application of embryogenic cell suspensions or the combined use of protoplasts with gene transfer or genome-editing techniques has enabled the development of new plant types with resistance or tolerance to the main diseases affecting the crop.

## Author Contributions

**J.R.L.M.:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **J.W.M.T.:** Funding acquisition, Supervision. **I.C.L.M.:** Validation, Project administration. **Y.A.O.G.:** Resources, Visualization.

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# Effects of lead and chromium on germination and root architecture of *Typha latifolia* (Typhaceae) seedlings

# Efectos del plomo y cromo en la germinación y arquitectura de raíz de plántulas de *Typha latifolia* (Typhaceae)

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**Abstract**

This research evaluates the effect of different concentrations of lead and chromium on root architecture and germination percentage of *Typha latifolia*. Seeds of *Typha latifolia* were collected from Yahuarcocha Lagoon (Ibarra-Ecuador). Pre-germinative treatments and exposure to lead concentrations of 50, 100, and 200 ppm, as well as 10, 20, and 40 ppm of chromium concentrations were applied to the seeds to measure the germination percentage. Regarding root architecture analysis, *T. latifolia* seedlings were grown for four weeks in 50 % Hoagland solution and then transferred to rhizotrons, where the heavy metals were added to concentrations like the germination test. The seedlings were kept in these conditions for 15 days and variables such as number of roots, total area, and total length were recorded. Photographic records of the parameters under study were taken and analyzed in Image J and its SmartRoot extension. It was found that both heavy metals affected (significantly) the germination process, especially chromium. Germination percentages lower than 15 % and 25 % for lead were also obtained. Concerning root architecture, the number of roots and total length from heavy metal treatments were not significantly different from control. However, the total area treatment with chromium showed significant differences with respect to the control.

***Keywords***: Plant physiology, heavy metals, aquatic plants, rhizotron, Yahuarcocha, *Typha latifolia*, Ecuador.

**Resumen**

El presente trabajo evalúa el efecto de diferentes concentraciones de plomo y cromo sobre la arquitectura de raíz y porcentaje de germinación de *Typha latifolia*. Para ello, se recolectaron semillas viables de dos sitios en la Laguna de Yahuarcocha (Ibarra-Ecuador). Con relación al porcentaje de germinación se trataron las semillas con procesos pre-germinativos; posteriormente fueron expuestas a concentraciones de 50, 100 y 200 ppm de plomo y 10, 20, 40 ppm de cromo. Para el análisis de la arquitectura de la raíz se cultivaron plántulas de *T. latifolia* por cuatro semanas en solución Hoagland al 50 %, luego fueron trasladadas a rizotrones en los que se añadieron los metales pesados en concentraciones similares al ensayo de germinación. Las plántulas se mantuvieron en dichas condiciones por 15 días en los que se registraron variables como el número de raíces, área total, y longitud total. Se realizaron registros fotográficos de los parámetros en estudio y fueron analizados en el programa ImageJ y su extensión SmartRoot. En el porcentaje de germinación se encontró que los dos metales afectan al proceso de germinación, especialmente el cromo, con el que se obtuvo porcentajes de germinación menores al 15 % y con plomo con un 25 %. Con respecto a la arquitectura de raíz el número de raíces y la longitud total no varió entre el control y los tratamientos con metales. Sin embargo, el tratamiento referente al área total de la raíz tratada con cromo presentó diferencias significativas con respecto al control.

***Palabras clave***: Fisiología vegetal, metales pesados, plantas acuáticas, rizotrón, Yahuarcocha, *Typha latifolia*, Ecuador.

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# 1 Introduction

Environmental pollution by heavy metals has increased significantly due to anthropogenic activities, particularly those derived from industrial practices. Since these contaminants are non-biodegradable substances, they exert lethal effects on plants, such as the reduction of transpiration rate and cell division (Sharma et al., 2022). In response to their exposure, plants exhibit decreased seed germination rates, inactivation of essential enzymes, and impairment of photosynthesis and water regulation (Zaidi et al., 2012). Moreover, heavy metals can alter plant morphology by reducing biomass, stem diameter, length, surface area, and soil distribution, as well as by decreasing the formation of lateral and adventitious roots (Baligar et al., 1998).

The root system of plant species plays a vital role in their growth and development, as it enables the absorption of water, nutrients, and minerals from the soil. For this reason, root architecture exhibits plasticity that depends on soil type and environmental conditions (Armengaud et al., 2009; Franco et al., 2011). The roots of plants tolerant to heavy metals and abiotic stress can respond not only to nutrient deficiencies but also to metal excess in the soil. This condition often leads to reduced growth parameters such as root elongation, biomass production, and root hair development, due to toxicity and the disruption of physiological processes (Barceló and Poschenrieder, 1992; Kahle, 1993).

Despite the detrimental effects of heavy metals, certain plants are known for their tolerance to these contaminants. Some are even capable of incorporating metals through absorption processes and storing them in the vacuole, thus avoiding the aforementioned physiological damages (Pal Singh et al., 2013). One such example is *Typha latifolia*, an aquatic species distributed throughout the Northern Hemisphere and introduced and naturalized in South America, East Africa, Australia, and Hawaii (Smith, 2018). Due to its high tolerance threshold, this species is considered a hyperaccumulator of heavy metals in its roots, with concentrations that may exceed those of the surrounding substrate (Branković et al., 2011). However, despite this tolerance, *T. latifolia* may still exhibit changes in root architecture and a gradual decrease in root growth depending on the concentration of metals to which it is exposed. Reported growth inhibition thresholds are in the range of 200–500 ppm for lead and 10–60 ppm for chromium (Sasmaz et al., 2008; Chen et al., 2014; Han et al., 2015).

Several techniques have been used to quantify these changes, among which root architecture analysis stands out. This method involves the systematic observation of measurable variables using instruments known as rhizotrons, which allow the manipulation of nutrient concentrations and other external factors (Busch et al., 2006). The description of the root system in plants grown in rhizotrons enables documentation of root growth and form, providing insight into their morphology, topology, and root–root interactions (Lobet et al., 2011). Furthermore, studying the seed germination of wetland plants tolerant to heavy metals, such as *Typha latifolia*, allows for determining the degree of seed resistance to contaminant exposure (Zhang, 2015), which is important in ecological restoration and environmental remediation projects.

Because of the latter, the objective of this study is to quantify the effect of different concentrations of lead and chromium on the seed germination and root architecture of *Typha latifolia* seedlings under laboratory conditions.

# 2 Materials and Methods

## 2.1 Seed Collection

Seeds of *Typha latifolia* were collected from spontaneously growing populations in Yahuarcocha Lagoon (2,200 m.a.s.l.), located in the province of Imbabura, Ecuador (Figure 1). Two collection sites were selected: the first, located on the northeastern shore of the lagoon (Site 1), locally known as "La vuelta de la paloma," and the second on the southwestern shore (Site 2), in the area referred to as "La recta de ingreso al poblado de San Miguel de Yahuarcocha."

From each plant, one mature inflorescence (dark brown in color, according to Smith (2018)) was collected, for a total of 20 inflorescences (ten per sampling site). The samples were stored under refrigeration at 3 °C for seven days. Seed collection was conducted during the rainy season between April and May 2021.

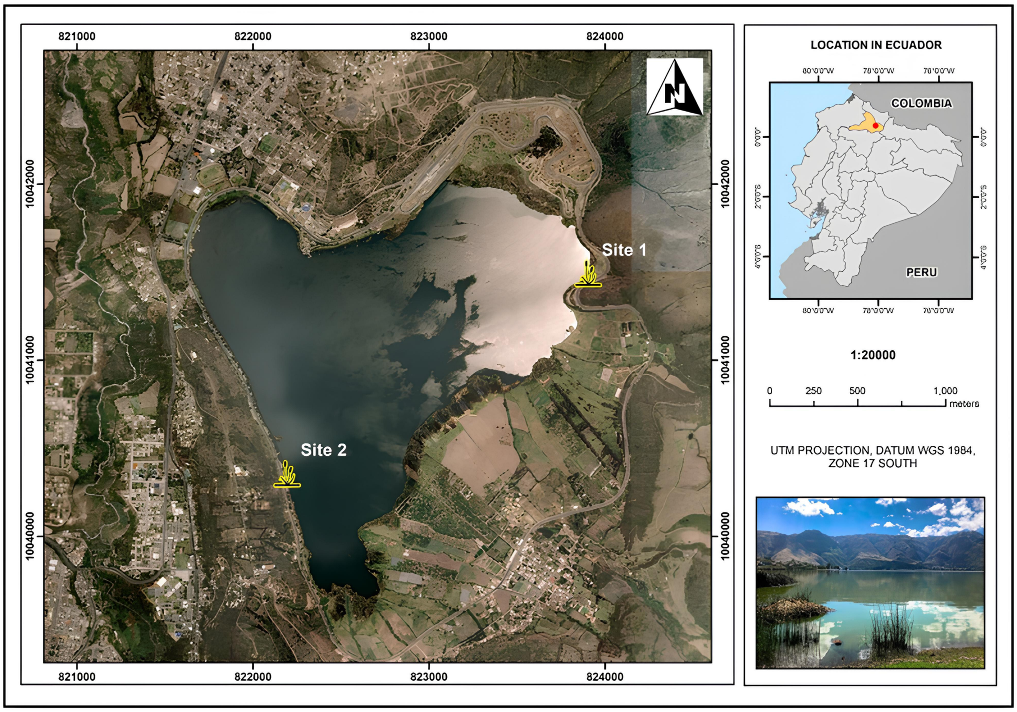


**Figure 1.** Seed collection sites of *T. latifolia* in Yahuarcocha Lagoon. Site 1: northeastern shore of the lagoon; Site 2: southwestern shore. Collection period: April–May 2021 (rainy season).

**Table 1.** Experimental conditions of the treatments in the germination test of *Typha latifolia* seeds collected from two sampling sites in Yahuarcocha Lagoon.

| Treatment | Replicates | Description* |
|---|---|---|
| Site 1 | 3 | 100 seeds from Site 1, hydrated in saline water (1 % NaCl) for 24 h, then hydrated in distilled water for 20 days. |
| Site 2 | 3 | 100 seeds from Site 2, hydrated in saline water (1 % NaCl) for 24 h, then hydrated in distilled water for 20 days. |
| Control 1 | 3 | 100 seeds from Site 1, hydrated in distilled water for 20 days. |
| Control 2 | 3 | 100 seeds from Site 2, hydrated in distilled water for 20 days. |

*General experimental conditions: pH between 6.5 and 7.5; photoperiod of 12 h light / 12 h dark; average temperature of 21 °C; hydration depth of 0.5 cm.

## 2.2 Seed Germination

The seeds, which range from 20,000 to 700,000 per spike (Smith, 2018), were disinfected using 2.5 % sodium hypochlorite (USDA, 2016). They were then placed in Petri dishes containing deionized water to separate viable seeds (those that sink) from non-viable ones (those that float) (Bourgeois et al., 2012).

A total of 600 viable seeds (300 from each site) were selected and placed in three Petri dishes (100 per dish). Each group of seeds was immersed in slightly saline water (1 % NaCl) with a pH between 6.5 and 7.5 for 24 h, following the recommendations of Semenova (2014) for this species.

Subsequently, the seeds were submerged to a depth of 0.5 cm in distilled water until germination, under a photoperiod of 12 h light / 12 h dark and an average temperature of 21 °C. No scarification treatment was applied, as reported by the Royal Botanical Gardens, Kew (2016), since this procedure reduces germination rates to below 58 % in *Typha latifolia*.

The control treatments consisted of 100 seeds from Site 1 (Control 1) and Site 2 (Control 2), hydrated in distilled water for 20 days, with three replicates each (Table 1).

The effect of lead on seed germination was evaluated by adding the following concentrations to each Petri dish: 50 ppm, 100 ppm, and 200 ppm, in the form of $Pb(NO_3)_2$, with three replicates (Table 2).

**Table 2.** Experimental conditions of treatments in the test assessing the effects of different lead (Pb) concentrations on the germination of *Typha latifolia* seeds collected from Yahuarcocha Lagoon.

| Treatment | Replicates | Description* |
|---|---|---|
| 0 ppm (control) | 3 | 100 seeds hydrated in distilled water without lead for 20 days. |
| 50 ppm | 3 | 100 seeds hydrated in distilled water with 50 ppm of lead for 20 days. |
| 100 ppm | 3 | 100 seeds hydrated in distilled water with 100 ppm of lead for 20 days. |
| 200 ppm | 3 | 100 seeds hydrated in distilled water with 200 ppm of lead for 20 days. |

*General experimental conditions: seeds hydrated in saline water (1 % NaCl) for 24 h prior to the addition of different lead concentrations; pH between 6.5 and 7.5; photoperiod of 12 h light / 12 h dark; average temperature of 21 °C; hydration depth of 0.5 cm.

To evaluate the effect of chromium on seed germination, concentrations of 10 ppm, 20 ppm, and 40 ppm were used in the form of $K_2Cr_2O_7$, with three replicates for each concentration (Table 3). In both experimental sets, the control treatments consisted of seeds hydrated in saline water (1 % NaCl) for 24 h as a pregerminative treatment, followed by hydration with distilled water.

**Table 3.** Experimental conditions of treatments in the test assessing the effects of different chromium (Cr) concentrations on the germination of *Typha latifolia* seeds collected from Yahuarcocha Lagoon.

| Treatment | Replicates | Description* |
|---|---|---|
| 0 ppm (control) | 3 | 100 seeds hydrated in distilled water without chromium for 20 days |
| 10 ppm | 3 | 100 seeds hydrated in distilled water with 10 ppm of chromium for 20 days |
| 20 ppm | 3 | 100 seeds hydrated in distilled water with 20 ppm of chromium for 20 days |
| 40 ppm | 3 | 100 seeds hydrated in distilled water with 40 ppm of chromium for 20 days |

* General experimental conditions: seeds hydrated in saline water (1 % NaCl) for 24 h prior to the addition of different chromium concentrations; pH between 6.5 and 7.5; photoperiod of 12 h light / 12 h dark; average temperature of 21 °C; hydration depth of 0.5 cm.

In the first experiment, the variable evaluated was the germination percentage of seeds from Sites 1 and 2 compared to the germination percentages of their respective control treatments (Control 1 and Control 2). In the second and third experiments, the germination percentage was assessed in treatments with seeds exposed to different concentrations of lead and chromium, respectively, as described above.

## 2.3 Root Architecture

To study root growth, a rhizotron was constructed with the following dimensions: 40 cm in front, 8 cm in width (lateral), and 40 cm in depth (in the direction of gravity) (Figure 2). The rhizotron was equipped with a double 5 mm thick glass front, allowing for temporal monitoring of root growth through photographic recording. On the surface of the growth medium (50 % standard Hoagland solution), a 4 mm cork sheet was placed, on which seedlings obtained from the control treatment of the germination experiment were positioned.

A total of three seedlings were transplanted into each rhizotron (45 days after germination), resulting in a total of 21 seedlings. Photographic records were taken at 0 (zero), 5, 10, and 15 days after transplantation (DAT). The rhizotrons were placed outdoors under sunlight at an approximate altitude of 2,220 m.a.s.l. and an average temperature of 20 °C.

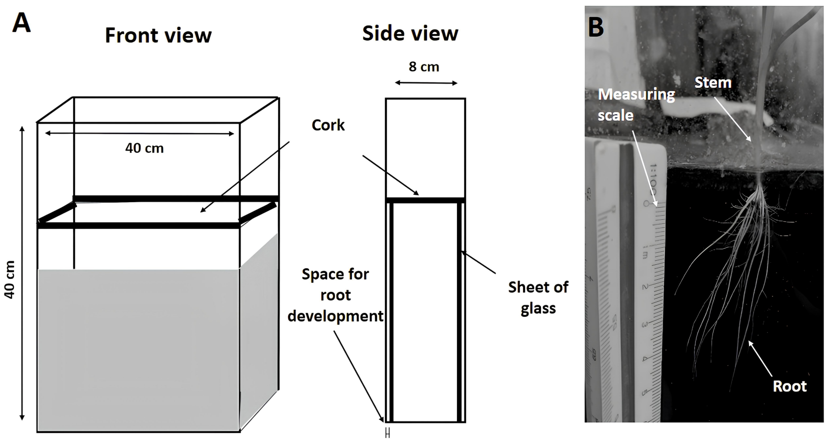


**Figure 2.** Characteristics of the constructed rhizotron. A. Dimensions of the container from the front and side views. B. Front view of a *Typha* seedling growing in the rhizotron.

## 2.4 Growth Conditions

Each rhizotron was filled with 8 L of half-strength Hoagland solution to simulate the natural conditions of the collection site (Hoagland and Arnon, 1938). Solutions were then added to achieve concentrations of 50, 100, and 200 ppm of lead and 10, 20, and 40 ppm of chromium. The concentrations of metal solutions were selected based on the species' tolerance reported in the literature and on the ranges of these metals found in previous studies characterizing the water, soil, sediment, and roots of *Typha latifolia* in Yahuarcocha Lagoon (Oquendo et al., 2020).

Control treatments consisted of seedlings grown exclusively in 50 % standard Hoagland solution. The germination and root architecture experiments of *Typha latifolia* were conducted at the Environmental Research Laboratory (LABINAM) of Universidad Técnica del Norte.

## 2.5 Image Analysis

Sequential photographs of all roots taken at the specified recording times (0, 5, 10, and 15 days after transplanting) were processed using the software ImageJ and its SmartRoot extension. The variables evaluated included: number of roots, total root area ($cm^2$), and total root length (cm) of the seedlings.

### 2.6 Statistical Analysis

Based on the data obtained for *Typha latifolia* seed germination percentage, the effects of lead and chromium on germination, and the effects of these heavy metals on root growth (in the rhizotron), three one-way analyses of variance (ANOVA) were performed. The first ANOVA compared the germination of seeds hydrated in distilled water (Controls 1 and 2) with that of seeds subjected to a pregerminative treatment (hydrated in 1 % NaCl for 24 h), for both Site 1 and Site 2. The second and third ANOVAs determined the effect of different heavy metal concentrations (lead and chromium) on the variables: germination percentage (in the second ANOVA) and number of roots, total area, and total root length (in the third ANOVA).

Subsequently, Tukey's multiple mean comparison test was applied for each ANOVA. The assumptions of normality and homogeneity of variances were verified using the Shapiro–Wilk and Levene tests, respectively. The level of significance used was 0,05, and the statistical software employed was Statistica version 10.

## 3 Results and Discussion

### 3.1 Germination

*Typha latifolia* seeds subjected to pregerminative treatment—hydrated in saline water (1 % NaCl) for 24 h and subsequently in distilled water for 20 days—showed a germination rate of $86{,}5\,\% \pm 9{,}2\,\%$ (standard deviation) for seeds from Site 1, while those from Site 2 exhibited a similar germination rate of $81{,}4\,\% \pm 5{,}9\,\%$. In contrast, seeds hydrated only in distilled water for 20 days showed lower germination percentages, decreasing to $60{,}4\,\%$ ($\pm 5{,}7\,\%$) for Control 1 and $57{,}2\,\%$ ($\pm 5{,}5\,\%$) for Control 2 (Figure 3).

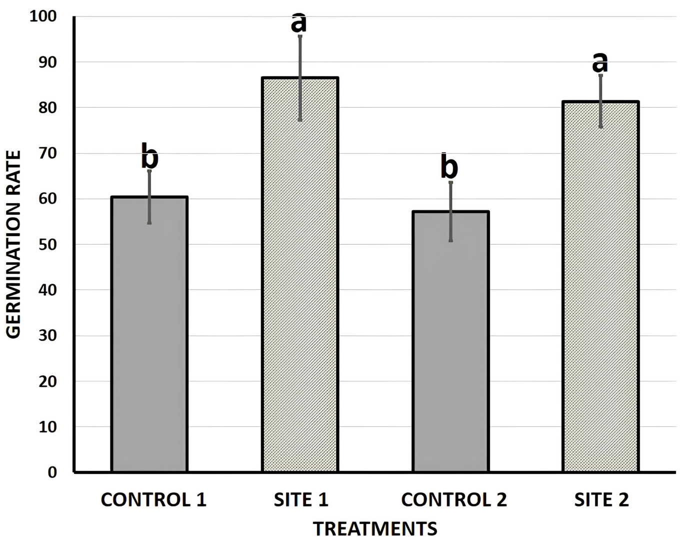


**Figure 3.** Germination percentage of *Typha latifolia* seeds from Yahuarcocha Lagoon. Control seeds (1 and 2, columns marked with b) were hydrated for 20 days, whereas seeds from Sites 1 and 2 (marked with a) were additionally subjected to a 24 h prehydration in saline water (1 % NaCl) as a pregerminative treatment. Different letters represent significant differences among treatments ($p < 0{,}05$).

No significant differences were observed between the germination percentages of seeds from the two collection sites; however, significant differences were found between the pregerminative treatments from both sites (columns a) and their respective controls (1 and 2), whose seeds did not receive pregerminative treatment (columns b).

Regarding the germination percentages under different concentrations of heavy metals during the hydration phase (Figure 4A), the results (presented with their respective standard deviations) for lead addition were $47{,}4 \pm 8{,}7\,\%$ germination at 50 ppm, $40{,}7 \pm 8{,}0\,\%$ at 100 ppm, and decreased to $22{,}1 \pm 4{,}8\,\%$ at 200 ppm of lead. The germination percentage of the control treatment (pregerminative + hydration) was $84{,}0 \pm 9{,}2\,\%$. Statistically significant differences were observed between the control (a), the 50 and 100 ppm concentrations (b), and the 200 ppm lead concentration (c) (Figure 4A).

For chromium, germination at 10 ppm was low, and it reached $25{,}4 \pm 7{,}3\,\%$. At 20 ppm, germination decreased to $18{,}2 \pm 5{,}3\,\%$, and at 40 ppm it further declined to $13{,}2 \pm 4{,}9\,\%$. The germination percentage of the control treatment (pregerminative + hydration) was again $84{,}0 \pm 9{,}2\,\%$ (Figure 4B). In this case, significant differences were found between the control treatment (a) and all three chromium concentrations (b): 10, 20, and 40 ppm.

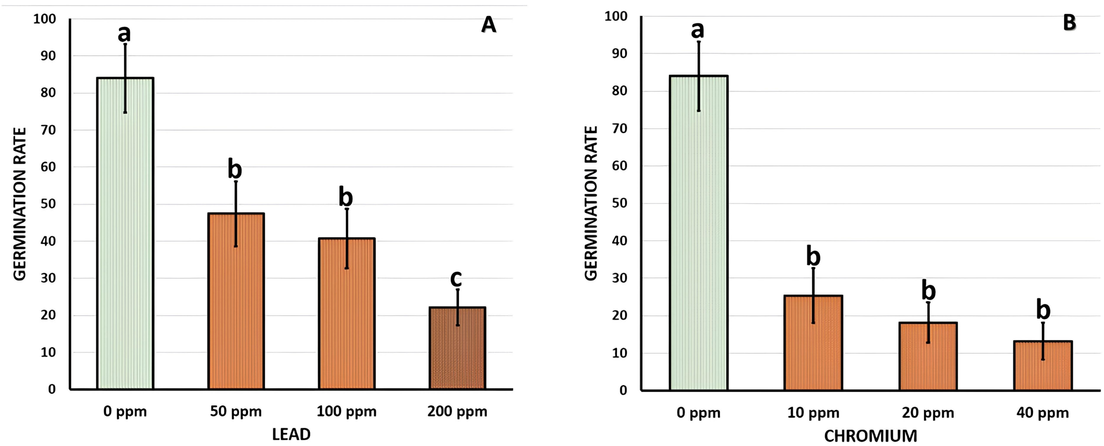


**Figure 4.** Percentage of *T. latifolia* seeds germinated under treatments: A) lead, and B) chromium. Mean values and standard deviations are shown. Different letters indicate significant differences according to Tukey's test ($p < 0{,}05$). The experiment was replicated three times ($n = 3$).

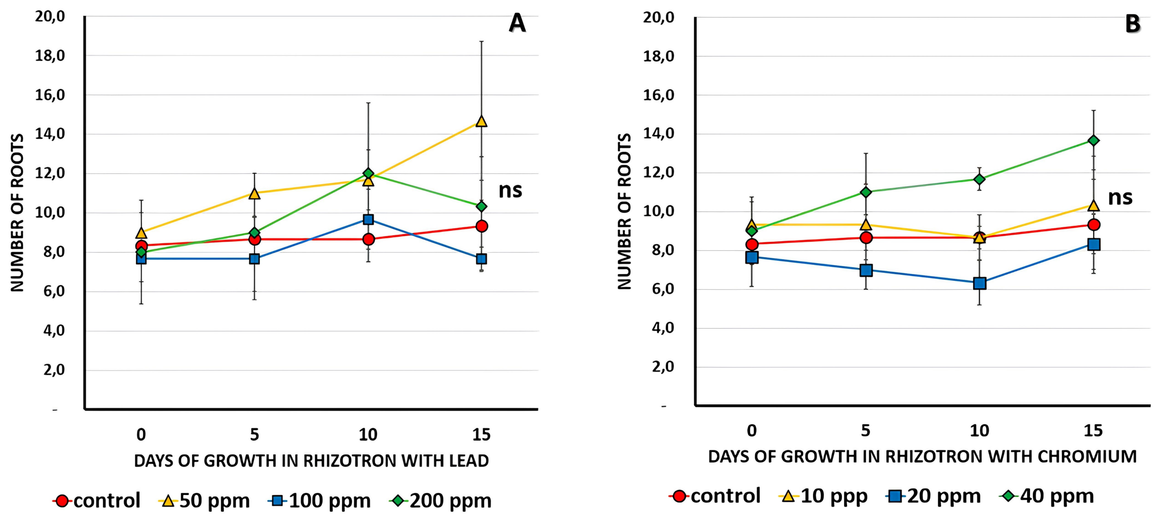


**Figure 5.** Variation in the number of *T. latifolia* roots in the presence of different concentrations of lead (A) and chromium (B) in the growth medium. Mean values and standard deviations are shown. No significant differences were found according to Tukey's test at $p < 0{,}05$; $n = 3$.

## 3.2 Root Architecture

When evaluating the effect of lead on the number of roots of seedlings grown in the rhizotron, no statistically significant differences (ns) were detected, although the absolute number of roots increased from the day of transplanting (0 DAT) to 15 DAT, when the evaluation concluded (Figure 5A). The results (all reported with their respective standard deviations) showed that the control treatment slightly increased the number of roots from $8{,}3 \pm 0{,}6$ to $9{,}3 \pm 2{,}3$ at 15 DAT. The highest increase occurred at 50 ppm of lead, from $9{,}0 \pm 1{,}0$ roots (at 0 DAT) to $14{,}7 \pm 4{,}0$ roots at 15 DAT. At 100 ppm of lead, the average number of roots remained constant ($7{,}7 \pm 0{,}9$) throughout the experiment. No significant differences were found among treatments (50, 100, and 200 ppm) or between these and the control (Figure 5A).

Similarly, a slight increase in root number was observed in the presence of chromium in the growth medium. However, unlike lead, the greatest increase occurred at the highest chromium concentration (40 ppm), where the number of roots increased slightly, from $9{,}0 \pm 1{,}7$ to $13{,}7 \pm 1{,}5$ by the end of the experiment (15 DAT), without significant differences. No statistically significant differences were found among chromium treatments (10, 20, and 40 ppm) or between them and the control (Figure 5B).

The average total root area ($cm^2$) increased by approximately three to six times over the 15-day evaluation period in all treatments—control and lead concentrations of 50, 100, and 200 ppm. The highest increase in total root area occurred at 100 ppm of lead, where values increased from $4{,}00 \pm 2{,}1$ $cm^2$ to $24{,}8 \pm 7{,}8$ $cm^2$. Conversely, the smallest increase occurred at 200 ppm of lead, from $6{,}5 \pm 3{,}3$ $cm^2$ to $13{,}4 \pm 7{,}7$ $cm^2$. However, no significant differences were detected among the four treatments (Figure 6A).

In the presence of chromium, no increase in total root area was recorded at any of the concentrations tested (10, 20, and 40 ppm), as the values remained constant (Figure 6B). Only the control treatment showed an increase in total root area, from $5{,}4 \pm 3{,}7$ $cm^2$ to $18{,}0 \pm 2{,}9$ $cm^2$, resulting in significant differences between the control (a) and all three experimental treatments (b).

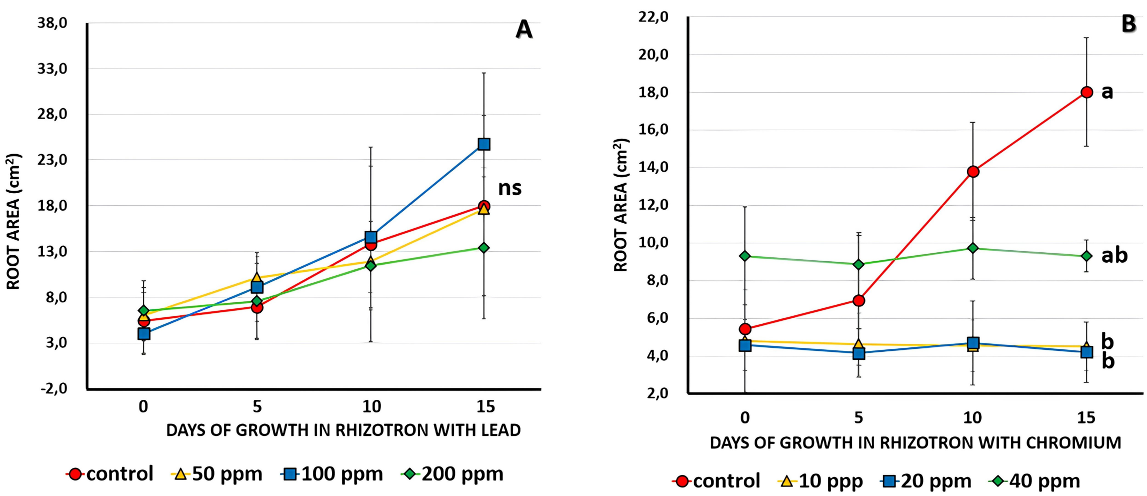


**Figure 6.** Variation in *T. latifolia* root area in the presence of different concentrations of lead (A) and chromium (B). Mean values and standard deviations are shown. Different letters indicate significant differences according to Tukey's test at $p < 0{,}05$; $n = 3$.

Total root length (cm) under different lead concentrations in the growth medium showed a steady increase throughout the experiment across all treatments. This increase was slightly higher at 50 and 100 ppm of lead, with values rising from $22{,}4 \pm 2{,}2$ cm at the beginning to $52{,}9 \pm 16{,}4$ cm at the end for 50 ppm, and from $19{,}2 \pm 3{,}5$ cm to $51{,}1 \pm 16{,}7$ cm for 100 ppm, respectively. No significant differences were observed among treatments (Figure 7A).

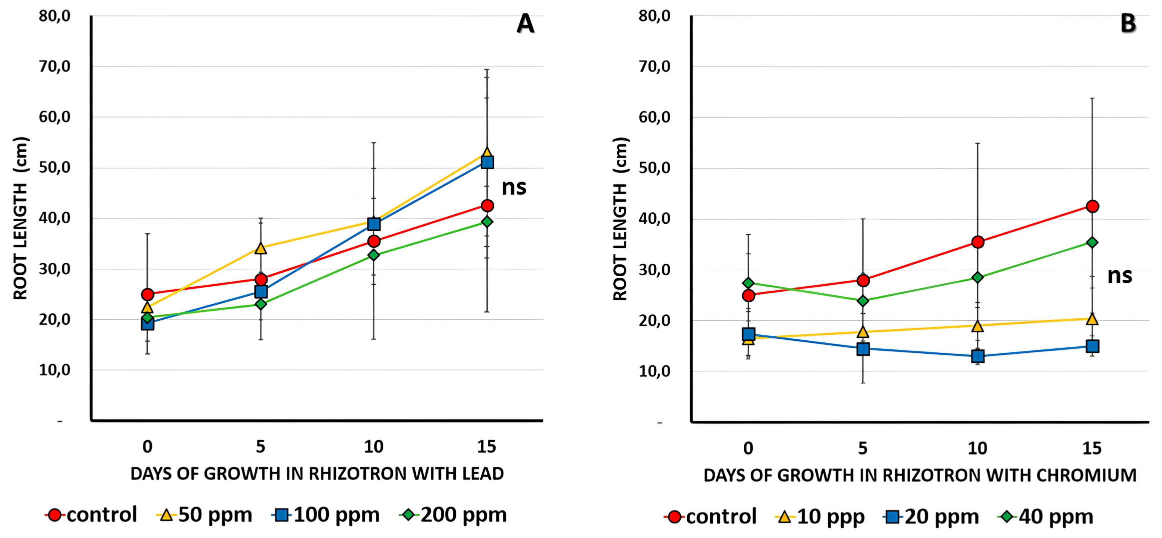


**Figure 7.** Variation in *T. latifolia* root length under different concentrations of lead (A) and chromium (B). Mean values and standard deviations are shown. No significant differences were detected according to Tukey's test at $\alpha = 0{,}05$; $n = 3$.

In contrast, the addition of chromium to the Hoagland solution caused an increase in total root length at 40 ppm (from $27{,}4 \pm 5{,}7$ cm to $35{,}4 \pm 6{,}8$ cm) and a slight increase at 10 ppm (from $16{,}5 \pm 3{,}6$ cm to $20{,}4 \pm 6{,}1$ cm). Conversely, at 20 ppm of chromium, total root length decreased from $17{,}4 \pm 4{,}9$ cm to $15{,}0 \pm 1{,}9$ cm during the 15-day evaluation period, likely due to the death of previously counted lateral roots, which reduced the final mean length. The greatest increase was observed in the control treatment, where total root length grew from $25{,}0 \pm 11{,}9$ cm to $42{,}6 \pm 21{,}2$ cm over the 15-day growth period (Figure 7B).

## 3.3 Discussion

Multiple factors can affect the mother plant during seed development and induce changes in germination traits (Baskin and Baskin, 2014). In this context, phenotypic plasticity is considered one of the principal mechanisms by which seeds adapt to changing environmental conditions (Gratani, 2014).

For instance, traditional germination of mature *Typha latifolia* seeds has been carried out by simple hydration in distilled water; however, a pregerminative hydration in 1 % NaCl solution for 24 h significantly increased germination relative to the traditional approach by an average of 25.2 %, consistent with the improvements reported by Semenova (2014). This solution may act by neutralizing potential germination inhibitors and delaying the growth of microorganisms that negatively affect germination (Lorenzen et al., 2000). According to the USDA (2016), *T. latifolia* seeds attain high germination percentages when proper procedures are followed, and mechanical scarification is not recommended: as noted by the Royal Botanical Gardens, Kew (2016), scarification does not enhance germination because cattail seeds are sufficiently water-permeable to trigger the process. The high germination percentage may be explained by the absence of dormancy in this species (Stewart et al., 1997), although Nishihiro et al. (2004) report physiological dormancy mechanisms in *Typha angustifolia*, a species closely related to *T. latifolia*, which could be common across the genus *Typha* (Baskin and Baskin, 2014).

No significant differences in germination were observed between the two sampling sites, likely because Yahuarcocha Lagoon is non-stratified: its waters mix throughout the year due to wind influence and inflowing streams, as indicated in the Lagoon Management Plan (IMI-UTN, 2012). Accordingly, based on *T. latifolia* germination, the two sites correspond to a single ecological population within the lagoon.

As for the effects of heavy metals on germination, the results (Figures 4A and 4B) show that both lead and chromium at the concentrations tested significantly reduced germination. Heavy metals often exert inhibitory effects on this process, as demonstrated by Oleszczuk (2008) and Pandey et al. (2008).

Lead, for example, reduced germination by 43 % at 50 ppm, and by 74 % at the highest concentration tested (200 ppm). This marked reduction may be attributable to lead (Pb), a non-essential metal that causes prolonged toxicity in plants, inducing adverse changes in seed morphology and germination as well as in enzymatic activities (Nas and Ali, 2018). These effects become more pronounced with increasing concentration and longer exposure. By reacting with sulfhydryl groups, lead inhibits enzyme activities and promotes the production of reactive oxygen species (ROS), causing oxidative bursts (Zulfiqar et al., 2019). In *Oryza sativa*, Gautam et al. (2010) found that reduced germination resulted from inhibition of $\alpha$-amylase activity, which in turn impaired starch degradation; similar effects may occur in grasses and graminoids (Sharma et al., 2022), including members of Typhaceae.

The reduction in germination was even greater in the presence of chromium: at only 10 ppm, germination decreased by 70 %, and at 40 ppm it declined by 85 %. Chromium's toxic effects compromise the physiology of seed germination (Zaranyika and Nyati, 2017). Nevertheless, Rout et al. (2000) showed that despite an initial reduction, seeds may develop tolerance and acclimation to chromium—particularly when mother plants originate from contaminated sites compared with uncontaminated ones—traits characteristic of hyperaccumulator species.

Heavy-metal tolerance also depends on plant genetics. Studies by Cheng et al. (2008) on 12 *Oryza sativa* genotypes and by Zhang (2015) on aquatic and marsh species such as *Phragmites australis*, *Arundo donax*, *Cyperus alternifolius*, and *Alisma plantago-aquatica* reported broad variability in adaptive responses, although the germination index generally decreased significantly as chromium concentrations increased. Pan et al. (2008) note that responses lacking predictable patterns at higher levels of cadmium, chromium, and mercury are genotype dependent.

Regarding root architecture, rhizotron experiments revealed structural changes in the *T. latifolia* root system in response to different concentrations of lead and chromium. The Hoagland solution used as the growth medium allowed assessment of root architecture while approximating the physicochemical and nutritional conditions of Yahuarcocha Lagoon.

Post-embryonic roots formed within five days after transplanting and continued to grow at 15 and 20 days post-transplanting, establishing a highly branched and functional root system.

For seedlings exposed to different lead concentrations, the average number of roots did not decrease—even at 200 ppm (Figure 5A)—indicating strong tolerance to this metal. Similar findings were reported by Buta et al. (2011) in *Eichhornia crassipes* exposed to lead, where root development did not decline, supporting its status as a tolerant aquatic species utilized in wastewater treatment.

In contrast, studies in the aquatic species *Hydrocotyle umbellata* reported that exposure to chromium and lead at varying concentrations reduced total biomass productivity; at high chromium concentrations, roots turned dark brown and leaf necrosis occurred (Yongpisanphop et al., 2005). Likewise, in *Fagus sylvatica*, root elongation and biomass were significantly reduced in soils containing 44 ppm lead, and root architecture exhibited abnormal morphology with strongly inhibited root hair development (Breckle and Kahle, 1992; Kumar Yadav et al., 2021).

In *T. latifolia* seedlings exposed to chromium, the average number of roots did not decrease, again indicating tolerance to this heavy metal. However, by the end of the experiment, many seedlings displayed abnormal (stunted) root growth and pronounced leaf yellowing. In a comparable study in which *Arabidopsis thaliana* seedlings were grown under different chromium concentrations, plants were more tolerant at lower concentrations; however, gradual increases in chromium led to growth inhibition (Martínez-Trujillo et al., 2013). Similarly, Ortiz-Castro et al. (2007) reported that chromium in the root system and architecture of *A. thaliana* seedlings at concentrations above 200 $\mu$M ($\approx$ 60 ppm—higher than in the present study) halted root growth and induced leaf chlorosis, an effect consistent with our observations.

Chromium is recognized as highly toxic to seedlings, impairing the absorption and transport of metals and nutrients from the soil, as extensively documented. For example, in *Pistia stratiotes*, chromium exposure produced toxic inhibition of growth, elongation, and normal root structure (Mufarrege et al., 2010); in *Cicer arietinum*, root length decreased progressively as chromium increased from 20 to 100 ppm (Medda and Kumar Mondal, 2017).

Root area (Figure 6A) and total root length (Figure 7A) increased slightly in the presence of lead, with no significant differences among treatments (including the control), corroborating the high tolerance of *T. latifolia* to lead and supporting its ecological use in removing nutrients and contaminants in natural or engineered water-treatment systems.

By contrast, chromium exposure halted seedling growth in the rhizotron throughout the 15-day evaluation, causing both total root area (Figure 6B) and total root length (Figure 7B) to remain constant. Meanwhile, the control showed a significant increase in root area, indicating normal growth when chromium is absent from the nutrient solution.

Overall, we found that both seed germination and root-system growth in *T. latifolia* exposed to lead persisted, indicating tolerance—at least for these two traits—and enabling survival in environments contaminated by this heavy metal (Branković et al., 2011). Seeds and seedlings exposed to chromium were less tolerant (in germination and root growth); however, tolerance may increase as plants develop under higher chromium concentrations (acclimation-based tolerance). These characteristics endow *T. latifolia* with attributes suitable for application in environmental remediation systems for contaminated waters.

## 4 Conclusions

Applying certain pregerminative treatments significantly increases germination percentage compared with seeds placed solely in distilled water. The *Typha latifolia* populations assessed likely belong to a single ecological population, as inferred from their germination performance under the applied treatments. Likewise, exposure to lead and chromium reduces germination percentage, particularly the latter.

Systematic use of rhizotrons enabled observation of sequential root development outside the natural habitat and control of key analytical variables. The metal concentrations tested did not alter root number or length; however, chromium exposure did affect total root area relative to the control, leading to the death of several seedlings—likely because reduced root area impaired processes such as water and nutrient uptake.

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## Author's contribution

**M.A.G.:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **A.V.S.:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **V.P.V.:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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Biotechnology

# Valorization of banana peel (*Musa paradisiaca*) as a raw material for biopolymer production

# Valorización de la cáscara de banano (*Musa paradisiaca*) como materia prima para la producción de biopolímeros

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**Abstract**

The use of plastic materials and their negative effects on society have increased studies on biomaterials as substitute materials. In the present research, a biofilm obtained from banana peel (PBCP) was developed, and subsequently, several properties were evaluated. By means of centrifugation, pulverized banana was extracted by varying the number of revolutions per minute (rpm): 900, 1500, and 3000. Glycerol was used for the formation of PBCP at concentrations of 30 % and 50 %; additionally, the heating temperatures were controlled at 70, 80, and 90 °C. The results showed that due to the low protein content of the pulverized banana, the treatments did not show thermal denaturation. The treatments subjected to 3000 rpm and 90 °C denoted higher viscosity values (57 570 Pa·s). On the other hand, in the analysis of moisture absorption kinetics, it was determined that the temperature and rpm variables did not influence the results obtained; however, the higher the percentage of glycerol in the film, the higher the rate of moisture absorption, going from $3.1 \times 10^{-10}$ to $3.7 \times 10^{-10}$ $cm^2/s$ and $3.9 \times 10^{-10}$ to $4.9 \times 10^{-10}$ $cm^2/s$, respectively. Regarding water vapor permeability, a significant difference in the levels of glycerol was evidenced; the PVA values of the PBCP in the different conditions ranged between 2.8 and 5.0 g·mm/(kPa·h·$m^2$). From the above, it is determined that it is possible to produce PBCP, and to improve the viscosity results, it is recommended to use an emulsifier to avoid the reagglomeration of the molecules.

***Keywords***: Biodegradability, biopolymer, plasticizer, production, rheology.

**Resumen**

El uso de materiales plásticos y sus efectos negativos en la sociedad ha incrementado los estudios acerca de biomateriales como materiales sustitutos. Durante la presente investigación se desarrolló una biopelícula obtenida a partir de cáscara de plátano (PBCP) y posteriormente se evaluaron varias propiedades. Mediante centrifugado se extrajo pulverizado de plátano variando el número de revoluciones por minuto (rpm): 900, 1500 y 3000. Para la formación de la PBCP se utilizó glicerol en concentraciones de 30 % y 50 %; adicionalmente, se controlaron las temperaturas de calentamiento en 70, 80 y 90 °C. Los resultados mostraron que, debido a la baja cantidad proteica del pulverizado de plátano, los tratamientos no muestran desnaturalización térmica; los tratamientos sometidos a 3000 rpm y 90 °C mostraron mayores valores de viscosidad (57 570 Pa·s). Por el contrario, en el análisis de cinética de absorción de humedad se determinó que las variables de temperatura y de rpm no influyen en los resultados obtenidos. No obstante, mientras mayor es el porcentaje de glicerol en la película, mayor es la tasa de absorción de humedad, pasando de $3,1 \times 10^{-10}$ a $3,7 \times 10^{-10}$ $cm^2/s$ y de $3,9 \times 10^{-10}$ a $4,9 \times 10^{-10}$ $cm^2/s$, respectivamente. En la permeabilidad de vapor de agua se evidencia una diferencia significativa en los niveles de glicerol. Los valores de PVA de las PBCP en las diferentes condiciones oscilaron entre 2,8 y 5,0 $g{\cdot}mm/(kPa{\cdot}h{\cdot}m^2)$. Por lo expuesto anteriormente, se determina que es posible elaborar PBCP y, para mejorar los resultados de viscosidad, se recomienda usar un emulsionante para evitar la reaglomeración de las moléculas.

***Palabras clave***: Biodegradabilidad, biopolímero, plastificante, producción, reología.

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# 1 Introduction

Globalized markets and consumer demands for products of not only hygienic-sanitary quality but also environmentally friendly traits have led the food industry to a paradigm shift in production in order to adapt to the needs of its clients (Ramos et al., 2020). One of the strategies used by the agro-industry to achieve this goal is cleaner production (CP), which allows the internal or external recycling of waste to increase process efficiency and reduce environmental risks (Hoof et al., 2018; Lucero-Murillo et al., 2026).

Another issue related to food production and consumption is the progressive use of disposable packaging, which—despite advantages such as low cost, resistance to oxidation, functional specificity, and versatility—causes a serious environmental impact (Mejía Osorio, 2020). Furthermore, according to Tuárez et al. (2022), additives incorporated to improve the functional properties of polymers used in packaging migrate into food, posing potential risks to human health. In this context, researchers are currently seeking substitutes for non-biodegradable packaging, and combined efforts have led to the development of biodegradable packaging produced from biopolymers (Ospina, 2015).

In the agricultural sector, the scale of waste is extensive, for example, crop residues and plant waste that remain in the field after harvesting (Mikus and Galus, 2022). Therefore, the main degradable biopolymers used for the development of edible films, coatings, containers, and food packaging are polysaccharides, with particular emphasis on derivatives of organic residues (Eixenberger et al., 2022).

For instance, Taghavi Kevij et al. (2021) developed functional edible films using gelatin and different concentrations (0, 3, 6, 9, 12, and 15 %) of powdered orange peel (POP). The thickness, moisture percentage, and water vapor permeability of the gelatin films increased as the POP content in the formulation increased. Films with higher POP content exhibited greater resistance and lower elongation. Moreover, their results demonstrated that the antioxidant content, particularly phenolic compounds, significantly improved with POP incorporation. Regarding antimicrobial activity, gelatin films against *Staphylococcus aureus* and *Escherichia coli* showed enhanced effectiveness with higher POP incorporation. These findings indicate that orange peel has strong potential for producing biopolymer films.

Another related study was carried out by Dao et al. (2022), in which pectin was extracted from coffee cherries. Although pectin constitutes approximately 50 % of coffee pulp, it is often not utilized, becoming one of the most abundant agricultural wastes in the food industry. The selected variety for this research was *Coffea arabica* L., from which pectin and cellulose were obtained using an eco-friendly method. The results showed that extraction with an acidified solvent at a pH of 3.1 and 84.3 °C for 4.3 h allowed recovery of 16.7 % pectin from coffee pulp. On the other hand, applying a two-step procedure—steam pretreatment at 170 °C for 30 min followed by bleaching with $H_2O_2$ at 40 °C for 10 h—yielded 54 % cellulose recovery from coffee pulp. Biopolymer films obtained from mixtures of coffee pectin and microcrystalline cellulose exhibited a smooth surface, high transparency, tensile strength of 3 MPa, and elongation of 4 %.

Based on the evidence presented above, it has been established that biopolymers can be obtained from organic waste. Considering the high production of plantain in Ecuador (Pacheco et al., 2021), plantain peel (*Musa paradisiaca*) was selected for this research, which aims to develop and evaluate a biopolymer derived from a residue of the food industry.

# 2 Materials and Methods

## 2.1 Extraction of starch from plantain peel

The organic residue selected for this research was plantain peel due to its high carbohydrate content (Anhwange et al., 2009). The plantain peel was obtained in the city of Santo Domingo, Ecuador, collected from several vendors dedicated to the preparation and sale of *chifles*.
The peels were carefully washed with warm water to remove any foreign material, then sliced and chopped. After pretreatment, acid hydrolysis was carried out using hydrochloric acid. Subsequently, deionized water was added to a beaker containing the hydrolyzed pulp, which was left to rest for approximately 8 hours. The extraction process was performed using a centrifuge (DM0412P with a capacity of 100 to 4500 rpm), selecting three rpm levels (900, 1500, 3000) according to the study of Altemimi (2018), who also standardized the centrifugation time at 15 minutes.

The centrifuged samples were filtered through a 180 $\mu$m sieve. The filtrate was then allowed to settle, and caustic soda was added to separate the protein content from the starch and to neutralize the acidity of the remaining starch. Afterwards, deionized water was added several times to remove the excess of caustic soda through a washing process. The resulting wet starch was dried in a tray dehydrator (DESHI 10) at a standardized temperature of 55 °C for 6 h, based on the research of Juárez Chunga (2022). It was then pulverized (PULVERIZER 10, 1.5 HP motor) until 95 % of the powder passed through a 120 $\mu$m sieve, according to the Ecuadorian technical standard for wheat flour (NTE INEN 612, 2006). Finally, the pulverized material was vacuum-packed to maintain 10 % moisture content.

## 2.2 Preparation of plantain peel biopolymeric film (PBCP)

The preparation of plantain peel biopolymeric films (PBCP) was carried out under atmospheric conditions. Following the method used by Kim and Min (2012), the solution formed from the pulverized extract at different rpm (900, 1500, 3000) and 30 % or 50 % (w/w) glycerol was heated at 70, 80, or 90 °C for 45 minutes.
The films were molded by pipetting the mixture onto Teflon plates ($14 \times 10$ cm) placed on a leveled ceramic surface; the volume of the film-forming solution was selected to produce films with a thickness of 0.2–0.3 mm. After one hour, the film was placed in a temperature/humidity chamber at $23 \pm 2$ °C and 50 % RH for 48 hours.

## 2.3 Rheological analysis

The rheological properties of the films were determined following the method of Hendrix et al. (2012) using a rotational rheometer (RheolabQC) with a 45 mm stainless steel (304) parallel plate. The film-forming solutions were deposited on a Peltier plate, deionized water was placed in the solvent trap, and a layer of oil was spread around the outer edges of the suspensions to limit water evaporation. The elastic modulus ($G'$) and viscosity ($G''$) were determined while gradually increasing the temperature from 20 °C to 90 °C at a ramp rate of 1 °C/min. All measurements were validated under conditions of 1 rad/s frequency and 2 % strain.

## 2.4 Moisture Absorption Kinetics Analysis

The method of Talja, Helen, et al. (2008) was applied with some modifications. Film samples were prepared with dimensions of $5 \times 15$ cm, maintaining a thickness of $0.2 \pm 0.03$ mm, and subsequently subjected to $45 \pm 2$ °C in a drying oven over silica gel until the samples reached a constant weight. They were conditioned at $23 \pm 2$ °C in a desiccator with a saturated potassium nitrate solution to ensure 94 % RH. Moisture absorption (MA) was then calculated using the following formula:

$$AH(\%) = \frac{W_t - W_o}{W_o} \times 100 \tag{1}$$

Where $W_0$ and $W_t$ were the weights of the dry samples and the samples at time $t$, respectively. Subsequently, following the method of Talja, Helen, et al. (2008), the diffusion coefficient ($D$) for water in the film samples was calculated from the slope of $W_t/W_\infty$ using the following equation:

$$D = \sqrt{\frac{t}{L^2}} \times \frac{W_t}{W_0} \times 0.6 \tag{2}$$

Where $L$ is half the thickness of the film and $W_\infty$ is the weight of water absorbed at equilibrium.

## 2.5 Water Vapor Permeability

The water vapor permeability (WVP) of the film was measured according to the ASTM E96-92 method of the American Society for Testing and Materials (McHugh and Krochta, 1994). Briefly, 6 mL of distilled water were added to a polymethyl acrylate sample cup (inner diameter: 46 mm, outer diameter: 87 mm, length: 21 mm), which was then hermetically sealed with the plantain peel biopolymer film (PBCP). The sample cups were placed in a static temperature chamber at $23 \pm 2$ °C equipped with fans adjusted to an air speed of 152 m/min. In addition, relative humidity (RH) was recorded with a hygrometer (Model THDx).

## 2.6 Biodegradability Test

The biodegradability of the biopolymer films was evaluated at room temperature over a period of 30 days, following the procedure applied by Iguardia (2013). The tests performed included outdoor degradability and river water degradability. For the first test, the samples were weighed and placed in uncovered glass containers to remain outdoors for 30 days. For the river water biodegradability test, the samples were weighed and immersed in a glass container with water; the containers were sealed, and the samples were left to rest for 30 days. After this period, the samples were weighed, and the biodegradability percentage was calculated using Equation 3:

$$\%\,\text{Biodegradability} = 100 - \left(\frac{\text{final weight}}{\text{initial weight}} \times 100\right) \tag{3}$$

## 2.7 Statistical Analysis

All measurements were calculated as the average of three values. The treatment factors in this study were: Factor A, the different rpm levels (900, 1500, 3000) at which the plantain peel powder was obtained; Factor B, the 30 % or 50 % (w/w) glycerol added to the formulation; and Factor C, the film heating temperature 80, 90, and 100 °C. Therefore, a completely randomized design with a factorial arrangement ABC was applied, resulting in 18 treatments with 3 replicates each, giving a total of 54 experimental units.

# 3 Results and Discussion

## 3.1 Rheological analysis

For the analysis, the initial temperature of the suspensions was 20 ± 2 °C, and the temperatures during the rheological tests ranged from 20 °C to 90 °C, with increased temperature ranges ($\Delta T$) of $20 \pm 1$, $25 \pm 2$, and $\pm 25$ °C and an approximate duration of 50 seconds.

The $G'$ values of the PBCP suspensions homogenized at 1 atm are presented in Figure 1. The $G'$ values decreased as the temperature increased from 20 °C to 90 °C. Temperature alters the size distribution of biopolymer aggregates/particles as well as the aggregation structure (Sanchez et al., 1999).

Suspensions formulated from starch centrifuged at 3000 rpm exhibited higher $G'$ values than the other treatments. In this regard, Tatirat and Charoenrein (2011) reported that acid hydrolysis and accelerated centrifugation may cause the breakdown of biopolymers. The decreasing pattern of $G'$ values for the suspensions could be explained by the loss of network structure within the PBCP polymers. A higher rpm during the extraction process of plantain peel biopolymer may result in the loss of the biopolymer network and consequently a decrease due to the high energy potential. However, the reduction rates of the suspensions treated at 900, 1500, and 3000 rpm were relatively small (Figure 1), and better $G'$ results were obtained with 30 % glycerol.

According to Sanchez et al. (1999) and later Hendrix et al. (2012), the regrouping of small particles slowed the rate of biopolymer network loss because immediately after treatment the biopolymers in the homogenized suspensions were very small. Nevertheless, these small biopolymer particles could rapidly regroup and form networks through hydrogen bonding, hydrophobic interactions, and charge–charge interactions, particularly when glycerol is used as the plasticizer.

In the present study, the rheological test temperature gradually increased from 20 °C to 90 °C, a range selected because PBCPs are heated to this temperature during preparation. Heating may cause protein denaturation in the suspensions, enhancing protein–protein interactions and reducing their segmental mobility (Pérez-Gago, 2012). However, the influence of protein denaturation, which normally occurs at high temperatures and is manifested by an increase in $G'$, was not observed in this rheological experiment. This may be attributed to the low protein concentration (∼0.43 %) in the suspension. The results suggest that heating the samples between 70 °C and 90 °C for 45 min may induce thermal denaturation of proteins in the film-forming suspensions, but under this experimental condition, it was not critical to achieving the expected physical properties.

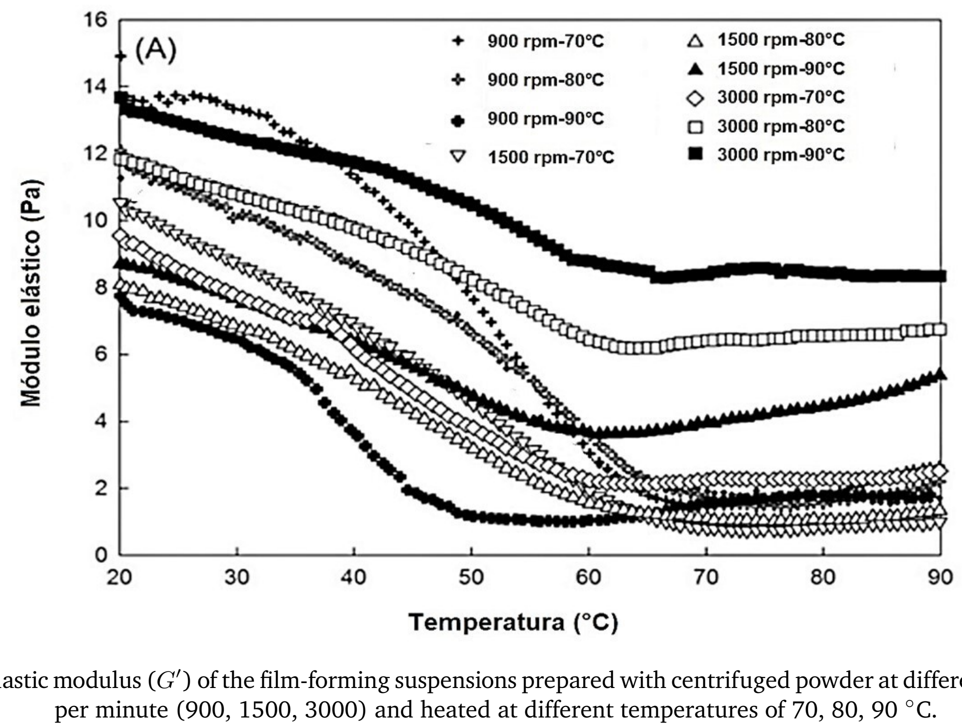


**Figure 1.** Elastic modulus ($G'$) of the film-forming suspensions prepared with centrifuged powder at different revolutions per minute (900, 1500, 3000) and heated at different temperatures of 70, 80, 90 °C.

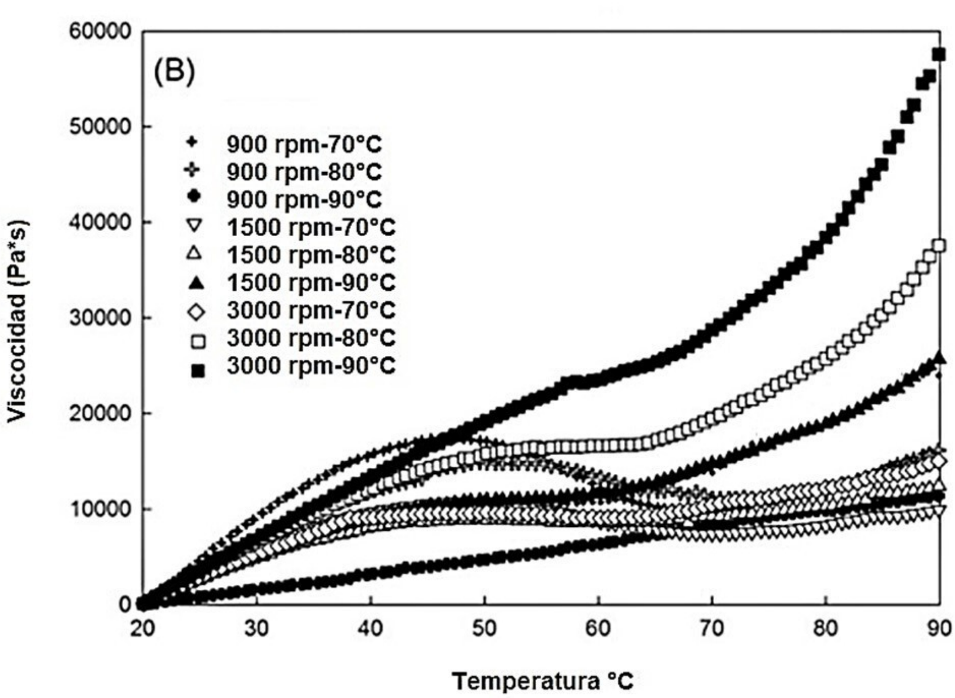


**Figure 2.** Viscosity ($G''$) of the film-forming suspensions prepared with centrifuged powder at different revolutions per minute (900, 1500, 3000) and heated at different temperatures of 70, 80, 90 °C.

The $G'$ values for all suspensions remained relatively constant between 4 and 8 Pa across the entire evaluated temperature range. Similar results were reported by Sablani et al. (2009) and Hendrix et al. (2012) in previous studies on film formation using biopolymer suspensions from apple peels and defatted mustard flour, respectively.

Regarding the suspensions prepared with powder centrifuged at 3000 rpm and at a film homogenization temperature of 90 °C, viscosity values were higher than those of the other treatments (Figure 2). Likewise, suspensions processed at 1500 rpm and 90 °C exhibited a viscosity profile similar to those prepared at 3000 rpm and 90 °C; however, the viscosity was significantly higher in the latter suspensions. In addition, the analysis showed that the higher the testing temperature, the greater the viscosity of the samples. A viscosity of 57,570 Pa·s was obtained in suspensions subjected to 90 °C, which was the highest value recorded. This may be attributed to increased intermolecular crosslinking between polymers, such as cellulose present in PBCP at elevated temperatures, resulting in gel formation (Coma et al., 2003).

## 3.2 Moisture absorption kinetics analysis

Regarding the results on water absorption, the samples conditioned at 94 % RH and 23 °C over time (Figure 3) revealed that water absorption was greater in PBCP containing 50 % glycerol, meaning that these films exhibited a wider hydration range. The inclusion of polar and hydrophilic glycerol molecules, which can act as strong hydrophilic centers that bind readily and firmly to water, likely results in an increase in surface hydrophilicity and facilitates water molecule absorption (Kang et al., 2015). Moreover, the similar polar and hydrophilic characteristics of water molecules and the biopolymer film matrices may lead to strong cohesion between molecules and matrices due to hydrogen bonding (Kang et al., 2015).

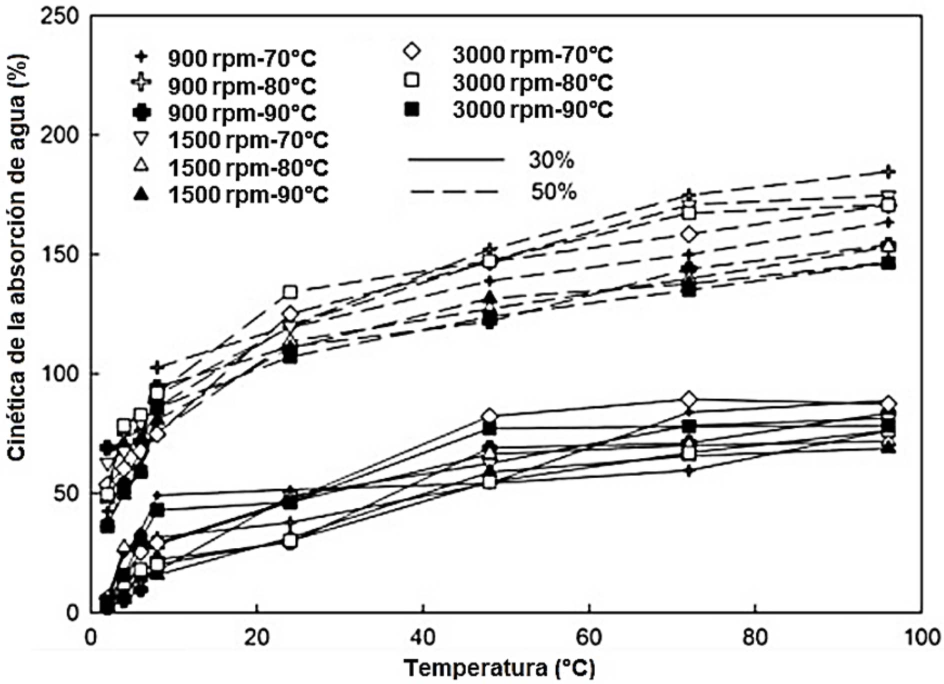


**Figure 3.** Water absorption kinetics of plantain peel-based films plasticized with glycerol formed from film-forming suspensions.

The water absorption results were strongly affected by the glycerol concentration but not by the heating temperature parameters or the centrifugation rpm prior to obtaining the powder (Figure 3). This finding is consistent with a previous study that demonstrated that the water absorption of biopolymer films made from apple peels was not affected by varying HPH pressure levels (138–207 MPa) or temperature (Sablani et al., 2009).

The $D$ values for the films studied, conditioned at 94 % RH and containing 30 % and 50 % glycerol, ranged from $3.1 \times 10^{-10}$ to $3.7 \times 10^{-10}$ $cm^2/s$ and $3.9 \times 10^{-10}$ to $4.9 \times 10^{-10}$ $cm^2/s$, respectively. The available volume for the expansion of water molecules in the film matrix increases as the amount of glycerol as a plasticizer increases. The present findings indicate that PBCP films can be formulated to provide a desired moisture migration rate by adjusting the amount of glycerol.

The $D$ values calculated in this study were comparable to those from other investigations in which biopolymer films were developed; for example, apple peel-based films ($0.82$–$2.62 \times 10^{-10}$ $cm^2/s$) reported by Sablani et al. (2009). However, these values are lower than those reported for microfibrillated cellulose films ($6.8 \times 10^{-10}$ $cm^2/s$) developed by Minelli et al. (2010), or the data ($12.6$–$31.8 \times 10^{-10}$ $cm^2/s$) presented by Taghavi Kevij et al. (2021) for keratin films, and they also differ from the $D$ values ($36.3 \times 10^{-10}$ $cm^2/s$) calculated for amylose starch films in the study of Muscat et al. (2014).

## 3.3 Water vapor permeability test

The WVP results of the films are shown in Table 1.

The thicknesses of the films containing 30 % and 50 % glycerol were $0.2 \pm 0.03$ mm and did not differ significantly ($p > 0.05$). WVP was generally higher in films with 50 % glycerol (Table 1), which may be explained by the fact that water vapor transmission through a hydrophilic film depends both on the diffusivity and the solubility of water molecules in the film matrix (Pak et al., 2020).

**Table 1.** Water vapor permeability (WVP) of plantain peel-based films.

| **Glycerol content** (% w/w) | **Powder centrifugation** (rpm) | **Heating temperature** (°C) | **WVP** ($g \cdot mm/kPa \cdot h \cdot m^2$) |
|---|---|---|---|
| 30 | 900 | 70 | 3.54 |
| | | 80 | 2.79 |
| | | 90 | 3.03 |
| | 1500 | 70 | 3.26 |
| | | 80 | 3.36 |
| | | 90 | 3.47 |
| | 3000 | 70 | 3.19 |
| | | 80 | 3.79 |
| | | 90 | 4.23 |
| 50 | 900 | 70 | 3.84 |
| | | 80 | 3.96 |
| | | 90 | 4.34 |
| | 1500 | 70 | 4.01 |
| | | 80 | 3.95 |
| | | 90 | 4.44 |
| | 3000 | 70 | 4.45 |
| | | 80 | 4.62 |
| | | 90 | 4.98 |

The higher WVP in films with 50 % glycerol compared to those with 30 % glycerol may result from decreased intermolecular attractions, greater spacing between molecular chains, and higher mobility within the film matrix due to the inclusion of more glycerol molecules between the polymer chains (Caicedo et al., 2022). The inclusion of glycerol could enhance water diffusivity through the PBCP film system by reducing the number of obstacles blocking water molecules as they pass through the biopolymer network (Sothornvit and Krochta, 2005).

The strong hydrophilicity of glycerol molecules, along with the different heating temperatures and centrifugation rpm, did not influence WVP at any glycerol concentration ($p > 0.05$). As described above, it can be assumed that particle size is reduced as revolutions per minute and temperature increase. A reduced particle size could decrease WVP, as under these circumstances it becomes more difficult for water molecules to find a pathway to diffuse through the matrix (Dangaran et al., 2006). However, in the present study, no such effect on WVP was observed with increased temperature or rpm in the films, which is likely due to the re-agglomeration of small biopolymer particles during film formation (García et al., 2020). The use of an emulsifier is suggested to prevent re-agglomeration.

The WVP values of PBCP films under the different conditions ranged between 2.8 and 5.0 $g \cdot mm/(kPa \cdot h \cdot m^2)$ (Table 2), which is comparable to previous findings using soy protein isolate, defatted mustard flour, fish gelatin, and apple peel, as reported by Sablani et al. (2009), Hendrix et al. (2012), Cho and Rhee (2004), and Kim and Min (2012), respectively. However, the WVP results of PBCP films were higher compared with studies that included methylcellulose (6.8 $g \cdot mm/(kPa \cdot h \cdot m^2)$), porcine skin gelatin (0.1–6.3 $g \cdot mm/(kPa \cdot h \cdot m^2)$), sodium caseinate (4.0 $g \cdot mm/(kPa \cdot h \cdot m^2)$), and beeswax (3.8–7.0 $g \cdot mm/(kPa \cdot h \cdot m^2)$), as referenced in the studies of Talja, Peura, et al. (2008) and Avena-Bustillos et al. (2006). On the other hand, Vargas et al. (2008) reported higher WVP values in studies using potato starch (8.0 $g \cdot mm/(kPa \cdot h \cdot m^2)$) and brown algae alginate (14.0 $g \cdot mm/(kPa \cdot h \cdot m^2)$). The high WVP in the present study can be attributed to the hydrophilic nature of PBCP polymers and the polar nature of glycerol. A high WVP could limit the use of these films for food with low or intermediate moisture levels (Valero-Valdivieso et al., 2013). Therefore, further research is suggested to develop methods for producing films with reduced moisture sensitivity that could be applied to foods with high moisture levels.

## 3.4 Biodegradability

Test According to the data obtained, the film prepared at 3000 rpm, heated at 90 °C, and containing 50 % glycerol showed the highest degradability both under outdoor conditions and in aqueous medium, with percentages of 47 % and 55 %, respectively. These values are comparable to the study conducted by Garcia (2019), which reported biodegradability percentages of 43 % to 47 % in biopolymer films over a one-month period.

# 4 Conclusions

Water absorption at equilibrium was higher and moisture barrier capacity was lower in films with 50 % glycerol. Therefore, since the moisture sensitivity of PBCP films was strongly influenced by glycerol concentration, the sensitivity of the film can be modulated by varying glycerol concentration. Regarding biodegradability, PBCPs showed values similar to those reported in other studies; however, their efficiency should be assessed under anaerobic conditions.

In addition, the use of an emulsifier is recommended to improve re-agglomeration, followed by new measurements to more accurately identify the effect of heating temperatures on the properties of plantain peel biopolymer films.

# Author Contributions

**J.T.:** Conceptualization, investigation, methodology, resources, supervision, validation, writing – review and editing. **R.J.:** Data curation, funding acquisition, project administration. **M.S.:** Formal analysis, visualization, writing – original draft.

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Biotechnology

# Optimization of the acid hydrolysis factors for obtaining glucose from banana, cacao, African palm, and sugarcane bagasse residues

# Optimización de los factores de hidrólisis ácida para obtener glucosa de los residuos de banano, cacao, palma africana y bagazo de caña de azúcar

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**Abstract**

Biomass is an alternative to provide energy sources that replace fossil fuels. The objective of this investigation is to optimize the conditions of the acid hydrolysis reaction for obtaining glucose from biomass: banana rachis, cacao pod, African palm rachis, and sugarcane bagasse. The conditions were evaluated through a $2^k$ experimental design. The factors studied were temperature, time, and acid concentration; the minimum and maximum levels correspond to 70 to 120 °C, 20 to 150 min, and 1 % to 5 % v/v, respectively. In addition, two replicates were made at the center. The best conditions for obtaining glucose were: 120 °C, 150 min and 1 % v/v sulfuric acid. Sugarcane bagasse and African palm rachis were the biomasses from which the highest glucose content was obtained, 9,936.48 and 7,745.14 mg $L^{-1}$, respectively. The influence of biomass composition on the amount of glucose obtained is discussed.

***Keywords***: Acid hydrolysis, biomass, glucose, structural characterization.

**Resumen**

La biomasa es una alternativa estudiada para proporcionar fuentes de energía que reemplacen a los combustibles fósiles. El objetivo de esta investigación es optimizar las condiciones de la reacción de hidrólisis ácida para la obtención de glucosa a partir de la biomasa procedente de los residuos de banano, cacao, bagazo de caña de azúcar y palma africana. Las condiciones fueron evaluadas a través de un diseño experimental $2^k$. Los factores estudiados fueron la temperatura, el tiempo y la concentración de ácido; los niveles mínimo y máximo corresponden a 70 a 120 °C, 20 a 150 min y 1 % al 5 % v/v, respectivamente. Además, se realizaron dos réplicas al centro. Las mejores condiciones encontradas para la obtención de glucosa fueron: 120 °C, 150 min y 1 % de ácido sulfúrico. El bagazo de caña de azúcar y el raquis de palma africana fueron las biomasas de las que se obtuvo el mayor contenido de glucosa 9.936,48 y 7.745,14 $mg\,L^{-1}$, respectivamente. Se discute la influencia de la composición de la biomasa en la cantidad de glucosa obtenida.

***Palabras clave***: Hidrólisis ácida, biomasa, glucosa, caracterización estructural.

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# 1 Introduction

The change in energy sources is a real challenge. Aiming for oil consumption reduction, the search for more sustainable materials with less environmental impact during their life cycle leads to selecting renewable raw materials or improving the processes used to obtain the final products. The use of lignocellulosic biomass, mainly derived from agricultural residues, has increased in recent years because these residues are renewable compared to the raw material of fossil origin (Thompson et al., 2017; Yánez-Iñiguez et al., 2020). However, the main restraint to its use is the lack of low-cost technology that can degrade the polysaccharides present in biomass. Thus, the lignocellulosic material can be converted into soluble sugars (Adsul et al., 2020; Loow et al., 2015; Faba et al., 2014). In Ecuador, there is a wide source of renewable raw material derived from the main permanent crops in this country, as indicated by the data presented in the 2014 Bioenergetic Atlas (Ministerio de Electricidad y Energía Renovable del Ecuador, 2014), and the main four are summarized in Table 1.

**Table 1.** Waste generated by permanent crops in Ecuador.

| Crop | Waste Tn/Year |
|---|---|
| African palm | 6,872,469.27 |
| Banana | 4,926,095.60 |
| Cocoa | 2,015,352.60 |
| Sugarcane | 793,283.38 |

The waste indicated in Table 1 can be from the field or processing, and it is possible to obtain second generation biofuels that do not involve a risk for food sources.

The lignocellulosic material consists of cellulose, hemicellulose, and lignin. These polymers contain many active functional groups capable of reacting (Odalanowska et al., 2021; Yogalakshmi et al., 2022). Cellulose polymers are glycoside units connected through $\beta$-1,4-glycosidic bonds, which are very stable and difficult to hydrolyze by the chemical or enzymatic route. Hemicellulose hydrolyzes more easily than cellulose and produces valuable pentoses, such as xylose and arabinose. Lignin has a very complex polymeric structure (Sun et al., 2016; Okolie et al., 2021). One of the leading and most common technologies for biomass treatment is acid hydrolysis; this method is preferred due to its low cost and effectiveness in the fractioning of hemicelluloses into monomeric while causing structural changes in the fractions (Loow et al., 2016). In general, sulfuric, hydrochloric, and nitric acids are used, although the last two are to a lesser extent. Treatments with high acid concentrations generate corrosivity problems, and their handling is dangerous. Hence, treatment with diluted acid is more applied (Hoang et al., 2021; Yuan et al., 2022). At an industrial level, biomass hydrolysis is a fundamental stage in obtaining second-generation biofuels, such as the specific case of bioethanol; therefore, the yield improvement towards monosaccharides, especially glucose will positively influence the subsequent manufacturing processes (Duque et al., 2021).

Glucose is the most abundant platform molecule of biomass in nature. Since it is the monomeric unit of the abundant biopolymer cellulose, it is considered a sustainable feedstock for producing carbon-based transportation fuels, chemicals, and polymers (Dutta and Bhat, 2022). Its water-soluble property makes it a promising alternative to produce valuable chemicals and biofuels efficiently. The C6 products obtained from glucose are suitable because their syntheses have a 100 % carbon economy (Liu et al., 2015).

Table 2 shows some results of different investigations, verifying that diluted sulfuric acid is the most used; however, the factors that intervene in the reaction of both temperature and time are high, which entails higher energy consumption.

The aim of this research is to take advantage of the residual biomass obtained in large quantities in Ecuador, mainly generated from banana, cocoa, African palm, and sugar cane crops, and to provide alternatives for their use in the production of biofuels or other derived products, which will contribute positively to the energy industry development in the country so that it is economically, technically, and environmentally sustainable. For this, the dilute acid hydrolysis process is studied, through an experimental design that optimizes the values of temperature, time, and acid concentration to maximize glucose conversion. Besides, the interactions between factors are statistically analyzed to determine their influence, which also favors decision-making regarding reaction conditions. In addition, each biomass is structurally characterized to obtain a database that allows knowing its composition and possible applications in industry, as well as its effect on the conversion to glucose.

**Table 2.** Results obtained from biomass hydrolysis processes

| Biomass | Acid | Temperature (°C) | Time (min) | Concentration (%) | Glucose ($g \cdot L^{-1}$) | Bibliographic source |
|---|---|---|---|---|---|---|
| Sugarcane bagasse | Sulfuric acid | 90 | 60 | 0.5 | 0.65 | (Roslan and Salimi, 2020) |
| Sugarcane bagasse | Sulfuric acid | 122 | 24 | 1 | 3 | (Dussan et al., 2014) |
| African palm rachis | Sulfuric acid | 210 | 5 | 0.8 | 6.27 | (Millati et al., 2011) |
| African palm rachis | Sulfuric acid | 100 | 240 | 6 | 1.43 | (Amirkhani et al., 2015) |
| Banana rachis | Sulfuric acid | 170 | 120 | 5 | 0.3 | (El-Zawawy et al., 2011) |
| Banana rachis | Hydrochloric acid | 150 | 280 | 3 | 0.4* | (Sathendra et al., 2019) |
| Cocoa pod | Sulfuric acid | 90 | 240 | 1M | 1.7 | (Samah et al., 2011) |
| Cocoa pod | Hydrochloric acid | 20 | 441.6 | 8.36 | 4.09* | (Shet et al., 2018) |

* Reduced sugars.

# 2 Materials and Methods

## 2.1 Reagents

Analytical grade sulfuric acid was purchased from Fisher Chemical (Center Valley, PA, USA). Analytical standard glucose and sodium chlorite were purchased from Sigma-Aldrich (St. Louis, MO, USA). Analytical grade ethanol, toluene, glacial acetic acid, and sodium hydroxide were purchased from Merck (Merck Darmstadt, Germany), Distilled water was obtained from a Water still WS 8000 (Boeco, Germany). Water type I was obtained from a Barnstead Water Purification System (Thermo Fisher Scientific, Kansas, USA).

## 2.2 Plant Material and Sample Preparation

The biomass from banana, cacao and oil palm plants were obtained from the crops of "Hacienda San José" located in Los Ríos province – Ecuador, km 8.5 Babahoyo - Febres Cordero at coordinates 1°53′15.7″S, 79°29′18.8″W. The banana variety used was *Musa Acuminate*, Cavendish subgroup of the AAA Group, Cocoa variety was CC N51, and African palm family Arecaceae, Liliopsida subgroup *Commelinidae*.

The sugarcane bagasse was obtained from a farm in the Yunguilla Valley, southwest of Cuenca at coordinates 3°17′58.843″S, 79°17′59.497″W, the variety was Canalpoa. The plants were cut down to collect the fruit bunch during harvest. The harvest area was delimited, and the residues were collected from twelve banana plants randomly distributed within the land area. Each plant was separated into its different parts: rachis banana, cocoa pod, rachis African palm and sugarcane bagasse according to their different physical-chemical characteristics; therefore, different monosaccharides concentrations were expected. Samples of approximately 300 g were taken from each part and were stored in hermetically sealed plastic bags for transportation to the laboratory, where they were cleaned up to remove any chemical residue (e.g., pesticides or insecticides) using pure water. The samples were then cut into sections of approximately 5 mm and dried in the oven (brand Innotech, model BJPX-Summer) at 105 °C until constant weight for approximately 24 hours. Then they were ground using a cutting mill (ALQUIMIA, model MC002) and sieved with a mesh, obtaining a particle size of maximum 5 $\mu$m. The prepared samples were stored in plastic bags at 2 °C until analysis.

## 2.3 Structural Characterization

First, the extractive and non-structural material from the biomass are removed to avoid interference with subsequent analytical steps (National Renewable Energy Laboratory, 2008). The extractives were eliminated according to the ASTM D1107 standard, using ethanol-toluene as solvent and the Soxhlet extraction equipment, the extraction thimble was placed with 7 g of sample and the flask was filled with 150 mL of solvent, the liquid was kept boiling for 7 hours, to later dry the sample to constant weight (ASTM International, 2021).

Once the extractible had been removed, the acid-insoluble lignin content was determined according to the TAPPI 222 standard (TAPPI, 2006). 1 g of the extract-free sample was used and 15 mL of 72 % sulfuric acid was gradually added. The carbohydrates were hydrolyzed and solubilized by sulfuric acid and the insoluble lignin is filtered, dried, and weighed.

To determine the percentage of holocellulose (cellulose and hemicellulose), the ASTM D 1104 standard was applied, which is obtained through the chlorination process eliminating the lignin, 2.5 g of extractive-free sample was used, 80 mL of hot distilled water, followed by 0.5 mL of acetic acid and 1 g of sodium chlorite, this addition was made 4 times (ASTM International, 1956). Cellulose was obtained from the holocellulose fraction, using the TAPPI 212 standard, which consists of treating 2 g of extractive-free holocellulose with 10 mL of 17.5 % sodium hydroxide for the degradation of hemicellulose and its content was determined from the difference between holocellulose and cellulose (TAPPI, 2002).

## 2.4 Experimental Design for Acid Hydrolysis Reaction

Acid hydrolysis was carried out in a batch reactor (THR 250 high pressure) with a 50 mL capacity, equipped with a pressure gage, temperature sensor plugs and mechanical stirring system. The material of construction is SS304L with Teflon coated to reduce corrosion from acid attack.

Monosaccharides were obtained from 3 g of biomass using 60 mL of acid aqueous solution (v/v). To study the influence of factors acid concentration, temperature, and reaction time on the amount of recovered glucose in the reaction, a $2^k$ factorial design was applied for each of the biomasses. Table 3 shows the three-factor design with two levels per factor applied to each biomass. Two replicates were made to the center. The factors: temperature, reaction time and acid concentration were tested in intervals of 70–120 °C, 20–150 min and 1–5 % v/v $H_2SO_4$, respectively. These conditions were applied for different biomasses (banana rachis, cocoa pod, african palm rachis and sugarcane bagasse) and the obtained solutions were filtered with Whatman N°54 paper and neutralized with 30 % (w/v) sodium hydroxide solution. After that, the samples were immediately analyzed in HPLC.

## 2.5 Chromatographic Analysis

Glucose concentration of the hydrolyzed plants residues was analyzed in an HPLC system (Jasco LC4000) equipped with a thermostat (Jasco CO4061), a refractive index detector (IR4030), a quaternary pump (PU4180) and a manual injector. The injection volume was 10 µL. The column used was VA 300 / 7.8 Nucleogel, Sugar 810 Ca, (300 × 7.8 mm) (Macherey-Nagel Germany). Column temperature, flow rate and concentration of sulphuric acid (mobile phase) were 85 °C, 0.5 mL/min and 0.01 % v/v sulphuric acid, respectively. Quantification was carried out using calibration curves of mix solutions of the tested monosaccharides in concentrations from 500 to 5,000 mg/L. Operation of the instrument and data processing were implemented using ChromNAV Ver.2.1.0 (Jasco Corporation, Tokyo, Japan).

## 2.6 Statistical Analysis

To determine the effects and significant interactions, the normal effects plot was used, with the effects found outside the line being considered significant. The individual and interaction effects were determined graphically. To obtain the linear models of each biomass, the assumptions of homoscedasticity and normality were verified through the normal quantile-quantile graphs, boxplot and the Shapiro–Wilk and Levene tests, results not shown; in all cases the assumptions were fulfilled. To determine the difference in means between biomasses, one-way ANOVA was applied. When significant differences were obtained with a significance level of 0.05, a post hoc test of mean difference was applied using the Bonferroni correction. The error was found through the replicas to the center. The R program version 4.0.4 with the R-studio interface was used for all analysis.

# 3 Results and Discussion

## 3.1 Structural Characterization of Biomass

Lignocellulosic material is mainly composed of cellulose, hemicellulose, lignin, ash, and extractable soluble in different solvents and impurities. For this study, the most relevant components in obtaining monosaccharides have been determined. Table 3 shows the results obtained for $\alpha$-cellulose, hemicellulose, insoluble lignin and ethanol-toluene extractables for each type of biomass. All these analyses were made in triplicate.

As seen in Table 3, when structurally characterizing the biomass, a higher $\alpha$-cellulose content was obtained in African palm with 48.11 %, followed by sugarcane bagasse with 46.19 %, and banana rachis with 31.40 %; these results are similar to those obtained by Kumneadklang et al. (Kumneadklang et al., 2019) who obtained 42.67 % for African palm while the study presented by Oliveira et al. (Oliveira et al., 2007) for banana rachis, it reaches 28.4 %. For hemicellulose, bagasse predominates with 28.64 %, a value similar to that presented in the Moraes Rocha investigations of 27.6 % (Dussan et al., 2014). The highest lignin content is presented by the cocoa pod, with 23.44 %, found within the range of 14–28 %, established in the studies of Lu et al. (Lu et al., 2018), the rachis of the banana has the minimum value of 7.67 %, compared to 9.6 % presented in the Oliveira studies. These percentages reflect that each biomass has a predominance in different components, which will influence the process towards glucose. Those biomasses with high contents of cellulose and hemicellulose will have a better yield in the conversion to monosaccharides.

**Table 3.** Structural characterization of banana rachis, African palm rachis, cocoa pod and sugarcane bagasse.

| Biomass | Holocellulose (%) | $\alpha$-Cellulose (%) | Hemicellulose (%) | Lignin (%) | Ext. Eth–Tol (%) |
|---|---|---|---|---|---|
| Banana rachis | 55.62 | 31.40 ± 0.519 | 24.23 ± 0.519 | 7.67 ± 0.001 | 3.49 ± 0.003 |
| African palm rachis | 71.00 | 48.11 ± 0.449 | 22.89 ± 0.449 | 14.97 ± 0.003 | 3.85 ± 0.004 |
| Cocoa pod | 40.90 | 25.54 ± 0.291 | 15.36 ± 0.291 | 23.44 ± 0.003 | 2.53 ± 0.004 |
| Sugarcane bagasse | 74.84 | 46.19 ± 0.290 | 28.64 ± 0.290 | 18.33 ± 0.007 | 5.71 ± 0.004 |

## 3.2 Acid Hydrolysis

In the results in Table 4, the highest amount of glucose was obtained with the sugarcane bagasse and the lowest with the banana rachis. Roslan et al. (Roslan and Salimi, 2020) used sugarcane bagasse biomass at a concentration of 1 % sulfuric acid, temperature of 122 °C for 24 minutes of reaction, obtaining a yield of $3\,\mathrm{g\,L^{-1}}$ of glucose. Dussan et al. (Dussan et al., 2014) also experiment with sugarcane bagasse, under reaction conditions of 90 °C, 60 min and a sulfuric acid concentration of 0.5 %, obtaining a maximum total sugar yield of $0.65\,\mathrm{g\,L^{-1}}$. The reaction conditions of those investigations with the present study are similar in temperature and concentration; however, the time variable is greater, being 150 minutes, which may influence the increase in yield obtained in this work. This amount of glucose could be used to obtain various value-added chemicals and biofuels; for instance: alcohols, gluconic acid, 5-hydroxymethylfurfural (HMF), lactic acid, pentanoic acid esters, 2,5-dimethylfuran (2,5-DMF). HMF can be converted into industrially useful chemicals such as furan and its derivatives, levulinic acid and formic acid, which are currently produced from petroleum resources (Liu et al., 2015; Bali et al., 2012).

The analysis of the interaction of the variables is described in Section 3.3.

**Table 4.** Factorial design $2^3$ with two replicas at the center.

| Labels | Factors | | | Glucose (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | a<br>Acid concentration | b<br>Temperature | c<br>Time | **Sugarcane bagasse** | **Banana rachis** | **Cocoa pod** | **African palm rachis** |
| (1) | -1 | -1 | -1 | 3,800.90 | 498.19 | 2,114.87 | 2,476.84 |
| a | 1 | -1 | -1 | 3,145.30 | 424.85 | 1,472.60 | 1,017.43 |
| b | -1 | 1 | -1 | 4,641.81 | 1,001.65 | 2,680.75 | 6,297.29 |
| ab | 1 | 1 | -1 | 5,942.57 | **1,787.32** | 1,526.06 | 6,542.49 |
| c | -1 | -1 | 1 | 4,355.34 | 541.77 | 880.11 | 2,657.56 |
| ac | 1 | -1 | 1 | 6,417.91 | 451.76 | 849.67 | 3,089.24 |
| bc | -1 | 1 | 1 | **9,936.48** | 1,670.22 | **2,719.70** | **7,745.14** |
| abc | 1 | 1 | 1 | 1,800.71 | 1,552.54 | 1,701.08 | 1,427.80 |
| Rep1 | 0 | 0 | 0 | 7,118.53 | 1,220.17 | 1,615.34 | 5,888.72 |
| Rep2 | 0 | 0 | 0 | 7,375.05 | 1,297.92 | 1,452.47 | 5,554.95 |

Comparing the glucose results obtained with the structural characterization of each biomass, both the sugarcane bagasse and the African palm present the highest content of holocellulose, reflecting in a higher conversion to glucose. However, this is not replicated in the case of banana rachis and cocoa pod, since even though the cocoa pod has a higher content of holocellulose, its conversion to glucose is lower. It may be due to different factors in the composition of these biomasses, so additional studies must be carried out to identify these factors.

Nowadays, different pretreatment processes are investigated to enhance the yield with acid hydrolysis; using ionic liquids is among the most promising, since it has proven to facilitate biopolymers decomposition due to removing the structural protection of the hydrolysis centers. The second part of this investigation will consider using these liquids to improve yields and reduce energy requirements.

## 3.3 Statistical Analysis

In the results in Table 5, the highest amount of glucose was obtained with sugarcane bagasse and the lowest with banana rachis. There are statistically significant differences between the amount of glucose obtained by each biomass $p(2.47\text{e-}06) < 0.001$. The differences are found between the glucose value obtained between the sugarcane bagasse and the banana rachis and between the cocoa pod and the sugarcane bagasse with $p(0.000) < 0.001$ in both cases. Also, significant differences are found between the African palm rachis and the banana rachis and between the African palm rachis and the cocoa pod with $p(0.001) < 0.01$ and with $p(0.013) < 0.05$, respectively.

**Table 5.** One-way ANOVA and post hoc test

| Biomass | Mean (DE) |
|---|---|
| Sugarcane bagasse | 5,453.46 (2,380.42)$^{a, b}$ |
| Banana rachis | 1,044.64 (535.91)$^{a, c}$ |
| Cocoa Pod | 1,701.27 (642.86)$^{b, d}$ |
| African palm rachis | 4,269.75 (2,391.86)$^{c, d}$ |

For sugarcane bagasse, Figure 1a, only the time factor is statistically significant, and no interaction was significant. Analyzing the effects, glucose obtention is favored with the high levels of temperature and time factors and with the lowest level of acid concentration (see S1).

About double interactions, these were observed between concentration and temperature, where the highest glucose obtained was at low acid concentration and high temperature. Interaction between time and concentration was also found, where the same previous case occurred. The graphs of double interaction can be seen in S2. Acid concentration and the triple interaction have negative coefficients (see Table 6). As seen, the concentration at a high level of the acid reduces the yield and this is increased at higher temperature and/or reaction time.

**Table 6.** Model coefficients.

| **Coefficients** | **Sugarcane bagasse** | **Banana rachis** | **Cocoa pod** | **Afric an palm rachis** |
|---|---|---|---|---|
| Intercept | $3,800.9^{**}$ | $498.19^{*}$ | $2,114.9^{**}$ | $2,476.8^{*}$ |
| Concentration | $-655.6$ | $-73.34$ | $-642.3$ | $-1,459.4$ |
| Time | $554.4$ | $43.58$ | $-1,234.8^{*}$ | $180.7$ |
| Temperature | $840.9$ | $503.46^{*}$ | $565.9$ | $3,820.4^{*}$ |
| Concentration:Time | $2,718.2^{*}$ | $-16.67$ | $611.8$ | $1,891.1$ |
| Concentration:Temperature | $1,956.4$ | $859.01^{*}$ | $-512.4$ | $1,704.6$ |
| Time:Temperature | $4,740.2^{**}$ | $624.99$ | $1,273.7$ | $1,267.1$ |
| Concentration:Time:Temperature | $-12,154.7^{**}$ | $-886.68$ | $-475.8$ | $-8,453.6^{*}$ |
| Residual standard error | $181.4$ | $54.98$ | $115.2$ | $236$ |

Significant: $^{*}p < 0.1$ and $^{**}p < 0.05$

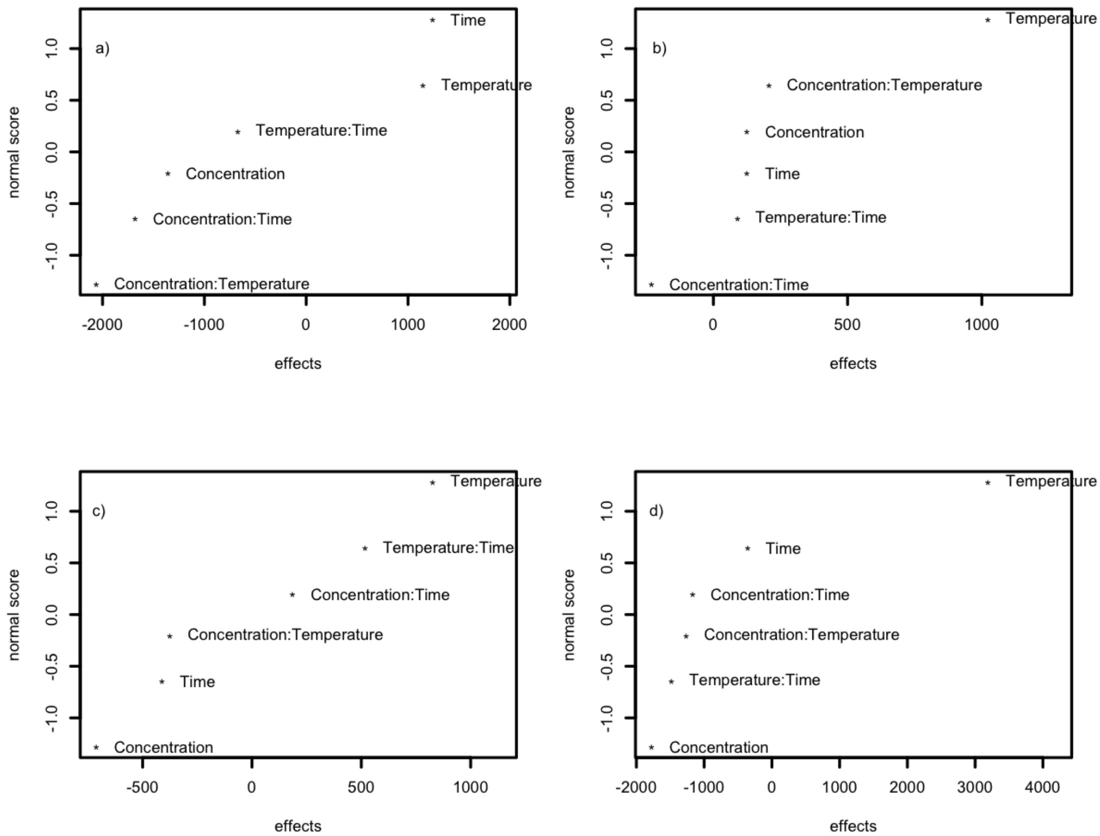


**Figure 1.** Analysis of interactions a) sugar cane, b) banana, c) cocoa and d) palm.

For banana rachis, Figure 1b, only the temperature factor was significant. Analyzing the effects, obtaining glucose is favored with high levels of the three factors, mainly with the temperature factor, since the other two levels do not vary too much their response between levels (see S1). Weak interactions between concentration-time and between temperature-time are found in both cases.

The best results are obtained with high temperature, and the levels of the other factors do not have significant influence. The acid concentration, the concentration-time interaction and the triple interaction have negative coefficients (see Table 6).

For the cocoa pod, in Figure 1c, neither the factors nor any of the interactions were significant. The simple effects show that obtaining glucose is favored by the high level of the temperature factor and with the low levels of the factor acid concentration and time (see S1). Double interactions were observed between time and temperature, where the highest glucose obtained was at the high temperature level, with no difference in time (see S2). Finally, the acid concentration, the temperature, the concentration-temperature interaction, and the triple interaction have negative coefficients (see Table 6).

In Figure 1d, for the rachis of African palm, only the temperature factor is significant. The simple effects show that obtaining glucose is favored with the high level of the temperature factor and with the low levels of acid concentration and time factors (see S1); being time the factor with the least influence. There is a temperature-time interaction, where the high-temperature factor is the one that produces more glucose. The acid concentration and the triple interaction show negative coefficients (see Table 6).

## 4 Conclusions

From the results obtained, it can be concluded that, in the case of cocoa pod, African palm rachis, and sugarcane bagasse, a temperature of 120 °C, a reaction time of 150 min and a concentration of 1 % sulfuric acid were the conditions that presented the best reaction yields. At these conditions, for the banana rachis a value of 1,670.22 $mg\,L^{-1}$ of glucose was obtained, while the best performance was given at a temperature of 120 °C, reaction time of 20 minutes, and acid concentration of 5 %, obtaining a value of 1,787.32 $mg\,L^{-1}$, the difference being 117.1 $mg\,L^{-1}$. In addition, it is shown that the structural composition of each type of biomass influences the obtaining of glucose; in this case, the bagasse being sugarcane and African palm rachis were those with the highest content of cellulose and hemicellulose.

In the statistical analysis for sugarcane bagasse only, the time factor is significant, while the high-level concentration of the acid impairs performance. For the case of the banana rachis and the African palm rachis, the temperature factor was significant. For the cocoa pod, neither the factors nor any of the interactions were significant.

Finally, the objective of this research was fulfilled, obtaining high yields of glucose conversion that allowed improving the subsequent biofuel manufacturing processes. A technical and economic feasibility study is recommended to achieve a balance between the amount of glucose obtained and manufacturing costs so that the process is profitable and can be applied on a large scale.

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## Author's contribution

**M.A.G.:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **A.V.S.:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **V.P.V.:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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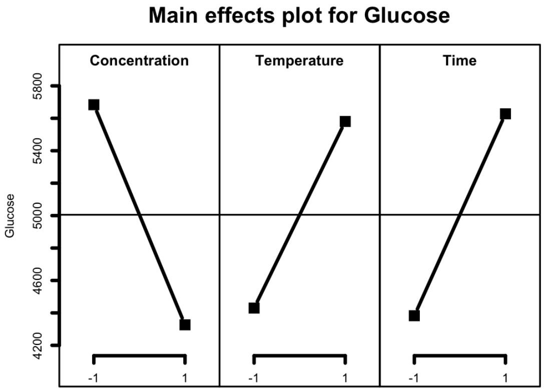
# Appendix

**S1. Main effects:** a) sugarcane bagasse, b) banana rachis, c) cocoa pod y d) African palm.

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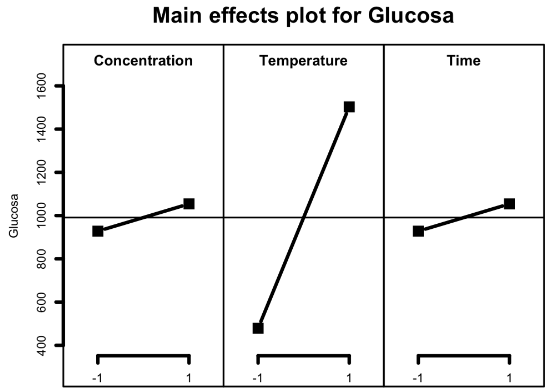


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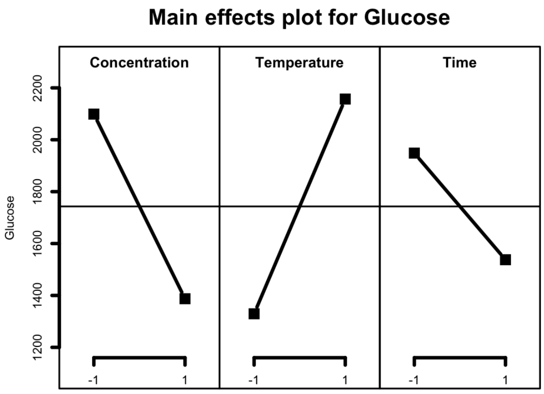


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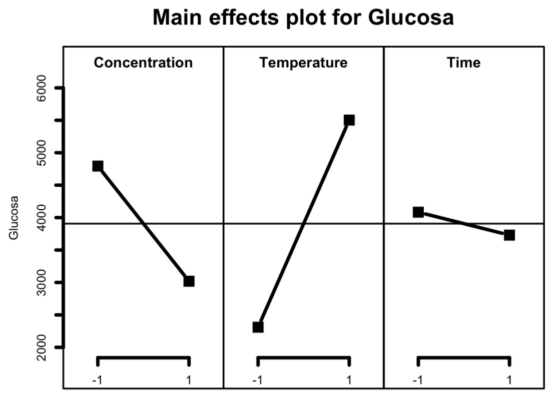
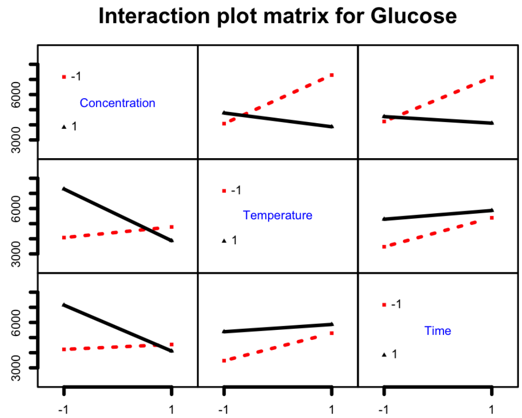



[d]

**S2. Interaction effects:** a) sugarcane bagasse, b) banana rachis, c) cocoa pod y d) African palm.

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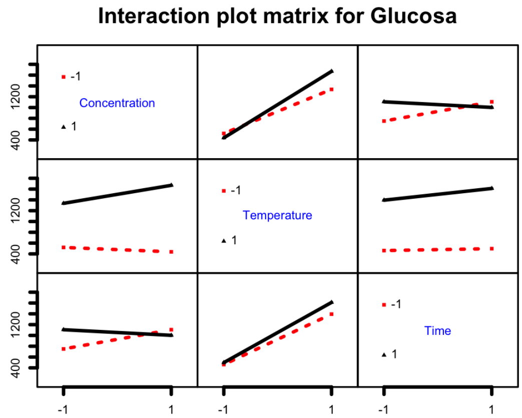


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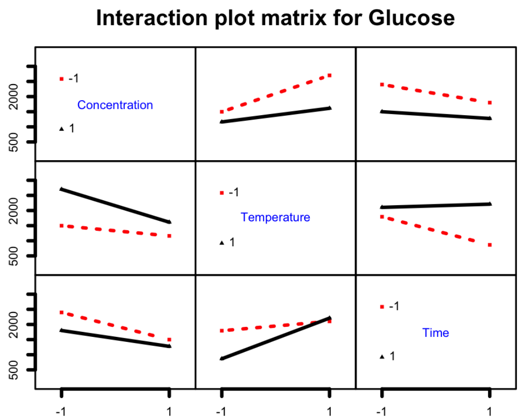


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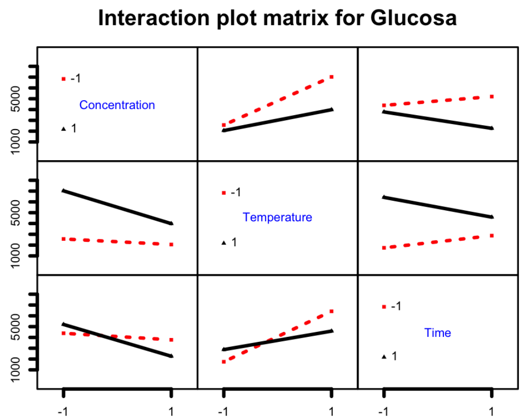


[d]

LA GRANJA:
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**SPECIAL ISSUE**
**Quality of life, development and social responsibility, climate change and the environment**

"Path to the Heights"

The grandeur of nature reminds us how small we are and how infinitely we can dream.
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## Fortalezas

*La Granja, Revista de Ciencias de la Vida* es la primera revista científica del Ecuador que aborda las temáticas de Ciencias Ambientales, de la Tierra y sus líneas transdisciplinares como Biotecnología, Ciencias Agropecuarias y Desarrollo Rural Sostenible, entre otras. Publicada por la Universidad Politécnica Salesiana en doble formato: impreso y on-line con periodicidad semestral, todos sus artículos se presentan en español e inglés. 24 años de edición y 310 artículos científicos publicados; editada por Abya-Yala con más de 48 años de experiencia en Ecuador.

La Granja tiene presencia en 96 bases de datos internacionales, plataformas de evaluación de revistas, directorios selectivos, portales especializados, catálogos hemerográficos, como: SCOPUS, ESCI, Emerging Sources Citation Index ESCI de la Web of Science, MIAR, EBSCO, LATINDEX, DOAJ, REDIB, DIALNET, REDALYC, BASE, entre otros.

Trabaja con un riguroso y transparente sistema peer review doble ciego de evaluación de manuscritos, sin costo, realizado por un consejo de revisión con 280 reconocidos investigadores de países de todo el mundo.

La administración de manuscritos se realiza a través del Sistema OJS 3, de la Fundación de Ciencia y Tecnología, con compromisos éticos publicados para la comunidad científica de transparencia y puntualidad; revisión de antiplagio realizada a través de Ithenticat y Similarity Check.

Alto nivel de visibilización con múltiples sistemas de búsqueda, DOI, ORCID, PDF dinámicos, xml jats, epub, con conexión a gestores documentales como Mendeley, RefWorks, EndNote y redes sociales científicas como Academia.edu y ResearchGate. Accesible digitalmente a texto completo, de forma gratuita, para toda la comunidad científica e investigadores de todo el mundo en apoyo a la política de Open Access y Early Access.

## Proceso de evaluación por pares

Todos los manuscritos deben ser consignados a través del sistema Open Journal System (OJS 3), que garantiza el registro electrónico y auditable de las interacciones entre la publicación y los autores. Una vez consignados, el Consejo de Editores revisa que los originales cumplan con el objetivo y alcance de la publicación, así como con las normas de autores.

El proceso de revisión íntegro, desde el momento del depósito de los manuscritos a través del OJS 3 hasta la finalización de las revisiones ocupa un tiempo medio de 12-16 semanas, salvo incidencias. Los revisores, a su vez, también deben cumplir unas normativas de revisores y el código ético de revisores.

## Antiplagio

Todos los manuscritos sometidos a revisión en La Granja Revista de Ciencias de la Vida, son inspeccionados por una disciplinada política antiplagio que vela por la originalidad de los artículos. Para ello se utilizan distintos servicios especiales como el sistema Ithenticate, que analiza los textos en busca de coincidencias gramaticales y ortotipográficas, lo que garantiza que los trabajos sean inéditos y asegura cumplir con los estándares de calidad editorial que avalen producción científica propia.

Asimismo, La Granja pone a disposición de autores y revisores, así como de la comunidad científica, un conjunto de herramientas específicas en la detección del plagio: Turnitin, Grammarly, Plagarisma.net, Viper Plagarism Scanner y Similarity (CrossCheck). Se trata de un conjunto de interfaces de libre acceso y de pago, que supervisan la originalidad de cualquier manuscrito y permiten controlar el plagio.

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