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MISCELLANEOUS

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Characterization of the environmental attitudes and practices of the urban population of Puno, Andean Plateau

Environmental regulations in eco-innovation and sustainable performance in Mexican automotive industry

Carihuairazo glacier retreat and its perception in the Cunucyacu community

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Dear readers,

When talking about sustainability, we are referring to a series of aspects that have become key elements in development planning across all levels globally for approximately four decades. Sustainability, or sustainable development, is a current paradigm that must be considered by all sectors, as it entails establishing a balance between the economic, social, and environmental aspects when addressing the development of societies.

Since its origin, there have been distinctions made regarding the use of either terminology. However, both terms are certainly valid, as stated in existing literature. They both constitute a concept coined in 1987 by Dr. G.H. Brundtland, head of the United Nations (UN), in the report titled "Our Common Future," and who introduced the term "sustainable development" (also referred to as "sustainability" in other texts). This expression encompasses the economy, the environment, and society as an interdependent trilogy, with the environment being the pivotal factor in decision-making (Gobierno de México, 2018).

Over the decades, sustainability has evolved in its theoretical understanding and has been the subject of analyses based on perspectives that weigh the existence of facts and circumstances. These circumstances, when not addressed or prevented, were not perceived as real until the consequences of such neglect became evident. These consequences manifest in various domains but are particularly perilous when overlooked by governments.

"…Omitting the issue of sustainable development in governmental systems' programs and strategic plans implies excessive expenditure, use, and abuse of environmental resources essential for the survival of living beings. Consequently, as the demand for products and services increases to meet the vital and common needs of society, coupled with the escalating lifestyle in large metropolises and various social strata, we observe how the longevity of human beings is being altered and affected (Alvarado-Peña and Echeverri De la Hoz, 2020, p. 14)."

In theory, and with the correct use of both concepts and terminologies, in Latin American companies or organizations, it is increasingly being acknowledged and understood, more so than in the past, that sustainable practices bring a set of benefits, both for the company itself (increasing and enhancing its value, performance, finances) and the significant economic and social impact for all parties involved. Therefore, the ultimate goal should always be to establish and strengthen objectives aimed at environmental conservation.

However, in practice, sustainable development is an aspect that has had little significance, even in the current era, mainly in those organizations whose resources, activities, production, and services are based on the exploitation of the environment. Organizations that inevitably move in a direction contrary to sustainable development "pose a clear threat to nature... but also to the humans who coexist with it" (Alvarado-Peña and Echeverri De la Hoz, 2020, p. 14).

Given the aforementioned, the ain of this work addresses the demands of the environment in terms of knowledge generation and scientific production, as well as the dissemination of research works in the social area that ultimately provide the necessary results for resolving various existing issues.

Research work on the topic of sustainable development, especially in the contexts of developing countries in the region, is a priority and a compelling reason to present some documents, products of researchers' concern and interest in disseminating information that precisely contributes to the solution of situations inherent in the promotion and strengthening of sustainability in organizations from various fields of knowledge. Therefore, we hereby present the different scientific articles, their titles, authors, and a brief description of their content:

ETHNOEDUCATION AS AN INSTRUMENT FOR THE PROMOTION OF SUSTAINABLE DEVELOPMENT. AN ANALYSIS FROM SCIENTOMETRICS

Presented by Hugo Semanate Quiñonez and Ciro Serna Mendoza, researchers from the University of Manizales and the National Training Service SENA, Colombia, this study comprises a comprehensive literature review of the most cited publications from 2017 to 2021, focusing on an analysis of ethno-education, contributions, and promotion of "sustainable development" through the pedagogical practices of Indigenous Peoples. The study yielded a total of 1,124 scientific documents annually, covering topics related to pedagogy, teaching, culture, and ancestral knowledge by prominent authors. The authors conclu-

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de that educational processes in ethnic communities arise from ancestral practices, thereby fostering sustainability. This approach allows for educating the "being" without conforming to developmentalist doctrines and educational models.

WILLINGNESS TO PAY FOR URBAN SOLID WASTE INTEGRAL SYSTEM IN SEMI-URBAN POPULATIONS

Researchers Francisco Iván Hernández Cuevas, Diana Estefanía Castillo Loeza, Javier Becerril García, and María Pía Mc Manus Gómez from the Universidad Autónoma de Yucatán and the Universidad Marista de Mérida in Mexico present a study, as described by the authors themselves, aimed at determining the socioeconomic factors associated with willingness to pay for the MIRSU (Integrated Management of Urban Solid Waste) among users in semi-urban municipalities of Yucatán (Mérida, Mexico). The study involved 1,144 surveys conducted in 6 semi-urban localities of Yucatán. The results revealed that respondents were willing to pay an average of 17.65 pesos for the integrated management of solid waste. It was observed that willingness to pay decreases when the Maya language predominates and when households have fewer physical assets and rooms. Among other findings, the study concludes that there are cultural and social elements ingrained in this behavior.

CHARACTERIZATION OF THE ENVIRONMENTAL ATTITUDES AND PRACTICES OF THE URBAN POPULATION OF PUNO, ANDEAN PLATEAU

Presented by Jesús Evaristo Tumi Quispe from the National University of the Altiplano Puno in Peru, this study aimed to characterize the pro-environmental attitudes and behaviors of the population of the city of Puno concerning sanitation, pollution, and environmental management. This non-experimental study was conducted among a population of 97,264 urban residents aged 18 and older. The results revealed that the environmental attitudes of most of the residents are positive regarding pollution factors, sources, and their effects on human health. The study concludes that new public policies in environmental education are required to effectively engage civil society, based on a system of incentives.

A HYDROPOWER DEVELOPMENT PERSPECTIVE IN ECUADOR: PAST, PRESENT, AND FUTURE

Researcher Sebastián Naranjo Silva from the Polytechnic University of Catalonia in Spain presents this research which aims to critically analyze the development of hydroelectric energy in Ecuador in recent years and establishes general energy projections for 2030 to expand knowledge fields and perspectives. Using a quantitative methodology, information was gathered from scientific publications, articles, research documents, and databases of governmental agencies regarding hydroelectric development in Ecuador and its regulations. As a result, through projection calculations, it is inferred that Ecuador will need around 43 TWh, 47 TWh, or 52 TWh by the year 2030 to supply the energy grid, depending on the proposed scenarios (low, medium, high). The study concludes that hydroelectric energy will indeed be fundamental to meet this requirement. However, there is a barrier for the country as hydroelectric energy is highly sensitive to external factors (climate effects), leading to an uncertain future.

ENVIRONMENTAL REGULATIONS IN ECO-INNOVATION AND SUSTAINABLE PERFORMANCE IN MEXICAN AUTOMOTIVE INDUSTRY

Conducted by Gonzalo Maldonado Guzmán, Víctor Molina Morejón, and Raymundo Juárez del Toro from the Autonomous University of Aguascalientes and the Autonomous University of Coahuila in Mexico, this study addresses a gap in the literature concerning the relationship between environmental regulations, eco-innovation, and sustainable performance in manufacturing companies. They aim to fill this gap and generate new knowledge through an extensive literature review. After analyzing data from a sample of 460 manufacturing companies in Mexico, the study concludes that environmental regulations have positive effects on eco-innovation, which in turn positively impacts the sustainable performance of automotive manufacturing companies. The study suggests that compliance with regulations leads to improvements in eco-innovation activities.

As a comment regarding the aforementioned studies, research on organizational sustainability is inherently complex and requires considerable effort, initiative, partnerships, and various inter-institutional relationships. It is crucial to recognize the valuable work done by researchers in this field, as they provide valuable information for general readers' understanding while disseminating new knowledge and laying the groundwork for future studies, which is already a significant achievement.

Furthermore, as La Granja is a miscellaneous journal covering Life Sciences, it also presents articles on various topics, including Earth Sciences, Veterinary Sciences, and Agricultural Sciences, which will be presented below.

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CARIHUAIRAZO GLACIER RETREAT AND ITS PERCEPTION IN THE CUNUCYACU COMMUNITY

In this research carried out by David Hidalgo, Jean-Carlos Ruíz, Luis Maisincho, Bolívar Cáceres, Verónica Crespo, Christian Domínguez, David Piedra, and Marcos Villacís, researchers from the IRD (Institut de Recherche pour le Développement), Sorbonne University, University of Grenoble, France; the Salesian Polytechnic University, the National Polytechnic School, the Andean University Simón Bolívar, and the National Institute of Meteorology and Hydrology of Ecuador, the retreat of glaciers in the Andes mountain range is analyzed, focusing on the significant loss of the remaining ice mass in Carihuairazo, which by 2021 has lost 99% of its total glacier surface. This comprehensive article not only analyzes meteorological and climatological data but also contrasts satellite images with interviews of community members from the surrounding area of Cunucyacu and mountaineers who work and frequent the area. Thus, it demonstrates how the Carihuairazo glacier is in a situation of inevitable disappearance and reveals the vulnerabilities of the communities facing this phenomenon.

LANDSLIDES SUSCEPTIBILITY ANALYSIS EMPLOYING ANALYTICAL HIERARCHY PROCESS ON AN AMAZONIAN ROADWAY IN ECUADOR

In the realm of Earth sciences, this article, presented by Cristian Cargua, Ronny Espin, Bryan Valencia, Marco Simbaña, Sebastián Araujo, Anderson Ocampos, and Carolina Cornejo, researchers from the National University of San Marcos in Peru, the Ikiam Amazon Regional University in Ecuador, and the Yachay University of Experimental Technology Research in Ecuador, addresses one of the most common issues in the Andean and Amazonian regions: landslides. Due to increasingly frequent heavy rains, exacerbated by the effects of climate change, indiscriminate logging, and the inherent geodynamic characteristics of the area, landslides and lahars are incurring a growing toll on infrastructure, roads, and even human lives.

This research focuses on the case of the Puyo-Tena Road, for which a cartographic model of landslide susceptibility was developed using variables such as slope, geological formations, land cover and use, as well as distances to faults, roads, and rivers. Handling multiple variables can pose a complex decision-making challenge. Therefore, an analytical hierarchy process, a semi-quantitative method that categorizes variables into five susceptibility categories easily understandable to decision-makers and the community at large, is employed. This approach enables relevant decisions to be made to mitigate potential events that could endanger the community.

MOLECULAR DETERMINATION OF THE ETIOLOGICAL AGENT OF BOVINE MASTITIS FROM ANDEAN PRODUCTION UNITS

In the field of veterinary sciences, Nancy Bonifaz, Ximena Galarza, Byron Fuertes, and Janss Beltrán, researchers from the Salesian Polytechnic University and the National Institute of Public Health Research in Ecuador, present one of the most comprehensive studies on bovine mastitis in the Andean regions of Ecuador. This study was conducted at the molecular level using the polymerase chain reaction (PCR) technique, which allows for the recognition of microbial family, genus, and species, as well as the detection of antibiotic resistance genes. This is crucial for diagnosing and treating diseases effectively. As a result, nine etiological agents causing the disease were identified, along with cases of resistance to several of the identified species.

RESPONSE OF FLOUR CORN (*ZEA MAYS* L. VAR. AMYLACEA) TO THE INOCULATION OF *AZOSPIRILLUM* AND PSEUDOMONAS

In the field of agricultural sciences, José Sangoluiza, José Zambrano, Misterbino Borgues, and Kang J. Cho, researchers from the Korea Program on International Agriculture (KOPIA), the National Institute of Agricultural Research (INIAP) of Ecuador, and the University of Granma in Cuba, present an agroecological alternative for fertilizing INIAP-101 flint corn. This alternative involves the use of beneficial bacteria residing in the plant rhizosphere due to their ability to produce phytohormones. These phytohormones promote greater nutrient absorption in the plant, leading to rapid vegetative growth and increased production without the need for chemical fertilizers. Thus, they propose a sustainable alternative for cultivating this corn variety in the region.

EFFECT OF PLANT DENSITY ON YIELD COMPONENTS OF COMMON BEAN GROWN UNDER INTER-ANDEAN MOUNTAIN CONDITIONS OF ECUADOR

Researchers from the National University of Loja and the Technical State University of Quevedo in Ecuador, including Santiago Vásquez, Edwin Villavicencio, Alex Guamán, Marlene Molina, and Camilo Mestanza, present a study on the factors determining bean yield by modifying grain sowing density. They found that density is a crucial factor in determining yield, including the number and weight of the grains studied.

We know that this selection of articles will be useful not only in the research conducted by our readers but also

as an overview of the scientific advancements in the field of Life Sciences occurring in the region. Scientific journals, such as La Granja, play a vital role in dissemination and disclosure, and being indexed in important databases poses certain challenges but also positions them as models of institutional integrity. These journals encompass sustainability and social responsibility, which are intriguing themes for the creation of research lines that explore studies evaluating and comparing high-quality dissemination platforms like La Granja journal.

We conclude by sharing an excerpt from an article that expresses and summarizes the relationship between the journal and the capacities it develops based on responsible practices, visible to all. It discusses the evolution of the concept of Corporate Social Responsibility (CSR) from philanthropy to sustainability, becoming a more elaborate concept that associates CSR with "responsible management of externalities, incorporating stakeholder expectations into management, creating shared value, and taking a leading role in building sustainable development..." (Daniel Licandro et al., 2019).

Sincerely,

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References

Alvarado-Peña, L. J. and Echeverri De la Hoz, D. (2020). Gerencia, investigación y desarrollo sustentable en las organizaciones de américa latina y el caribe (alc). *Revista Venezolana de Gerencia*, 24(12):13–16. Online:https://doi.org/10.37960/revista.v24i2.31482.

Daniel Licandro, O., Alvarado-Peña, L. J., Sansores Guerrero, E. A., and Navarrete Marneou, J. E. (2019). Responsabilidad social empresaria: Hacia la conformación de una tipología de definiciones. *Revista Venezolana de Gerencia*, 24(85):281–299. Online:https://doi.org/10.37960/revista.v24i85.23843.

Gobierno de México (2018). Diferencia entre sustentable y sostenible. secretaría de medio ambiente y recursos naturales. Gobierno de México. Online:https://n9.cl/zf30y.

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Special Issue / Edición Especial

Sustainable Development

Ethnoeducation as an instrument for the promotion of sustainable development. An analysis from scientometrics

La Etnoeducación como instrumento para la promoción del desarrollo sustentable. Un análisis desde la cienciometría

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Abstract

Ethno-education allows advancing towards interculturality, recognizing the diversity of cultures in Colombia; however, there is no evidence of a clear formative route as a social project that vindicates the knowledge of the communities and allows strengthening the processes of cultural identity necessary for the survival of the Indigenous Peoples. The objective of this work is to answer whether ethno-education contributes to the promotion of sustainable development from the pedagogical act of the Indigenous Peoples. For this, a literature review was carried out from the most cited publications from the years 2017 to 2021 in the *Scopus*, *Web of Science* and *Dimensions* databases, selected by the English language, Spanish and the keywords indexed in the UNESCO Thesauri dictionary. In the analysis of scientific production, the scientometric tools *RStudio-Cloud*, *Bibliometrix* and the *Tree of Science (ToS)* method were used. The *VOSviewer* and *Gephi* software were also used to identify the research subareas and generate the knowledge network. The work allowed marking the evolution of the annual scientific production with 1,127 scientific documents, the thematic map with emerging topics related to pedagogy, teaching, culture, ancestral knowledge, and the knowledge network forged by the most important authors for this work. As a main conclusion, it was identified that the educational processes should arise from the heart of the ethnic communities, which seek to transmit ancestral practices, promote sustainability, educate the being without adapting it to developmentalist doctrines and educational models.

Keywords: Bibliometry, Indigenous knowledge, Educational sciences, Sustainable development, Cultural diversity.

Resumen

La etnoeducación permite avanzar hacia la interculturalidad, reconociendo las diversidades de culturas con que cuenta el estado colombiano; sin embargo, no se evidencia una ruta formativa clara como proyecto social que reivindique el saber de las comunidades y que permita fortalecer los procesos de identidad cultural necesarios para la pervivencia de los Pueblos Originarios. El objetivo del trabajo es responder si la etnoeducación aporta a la promoción del desarrollo sustentable desde el acto pedagógico de los Pueblos Originarios. Para lograrlo se hizo una revisión literaria de las publicaciones más citadas de los años 2017 a 2021 en las bases de datos *Scopus, Web Of Science* y *Dimensions*, seleccionadas por el idioma inglés, español y las palabras clave indexadas en el diccionario Tesauros de la UNESCO. En el análisis de la producción científica se utilizaron las herramientas Cienciométricas *RStudio-Cloud, Bibliometrix* y el método de *Tree of Science (ToS)*. Asimismo, se manipuló los softwares *VOSviewer* y *Gephi* para identificar las subáreas de investigación y generar la red de conocimiento. El trabajo permitió marcar la evolución de la producción científica anual con 1.124 documento científicos, el mapa temático con tópicos emergentes relacionados a pedagogía, docencia, cultura, conocimientos ancestrales y la red de conocimiento forjada por los autores más importantes para este trabajo. Como conclusión principal se identificó que los procesos educativos deben surgir desde las comunidades étnicas, los cuales buscan transmitir las prácticas ancestrales, impulsar la sustentabilidad, educar al ser sin adaptarlo a doctrinas y modelos educativos desarrollistas.

Palabras clave: Bibliometría, Conocimientos indígenas, Ciencias de la educación, Desarrollo sostenible, Diversidad cultural.

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1 Introduction

Ethno-education emerged in the mid-1970s as a form of resistance of ancestral culture against education models focused on the development of the country, achieving gradual recognition by their communities, and generating interest to understand their culture from an ontological and epistemological perspective.

In must be taken into account the struggles of the classes that believe themselves to be minority in the country such as the Afro-American and native peoples, which still retain their traditional practices despite their constant struggle since the entry of the Spaniards in Latin America. Ethno-education in Colombia relates to the processes that determine the privileges of the Church in the ancestral territories, as well as the historical resistance of ethnic groups subjected to an official Catholic education that dissociates their cultures and ways of life (Molina, 2012), "whose educational process consisted of the Castilianization and deindianization of indigenous peoples" (Vitonás, 2010, p. 2).

Ethno-education originated in the First Peoples, at the root of Mother Earth, where the ethnoeducators not only teach, but are wise, medical doctors, guards and leaders who articulate the different processes in the communities in favor of the sustainability of the territories; it is the starting point that allows the radical reconstruction of the being, power and indigenous knowledge through their daily practices (Barragán-Varela, 2020). As a development of democracy, according to Mendoza-Castro (2010, p. 4) "ethno-education is an instrument that allows populations to inquire about the pedagogical, administrative and methodological strategies that best adapt to their way of living and their culture", which has been crucial for communities to have the opportunity to carry out ethno-educational programs, processes that recognize their culture and fulfill the objectives of safeguarding ancestral traditions.

Although since the creation of the Constitution of Colombia in 1991 there are improvements in ethnoeducational policies, such as Law 115 (Congreso de Colombia, 1994) that allows the right of official education, which focuses on teaching-learning, it continues to violate ethnic communities, forcing them to take the curriculum that does not include their imaginaries and cultural legacies.

The Indigenous Peoples also rely mainly on legal tools such as those provided by Decree 2500 of 2010 (Colombia, Presidencia de la República, 2010) that allows the development of the Indigenous Own Educational System (SEIP), a decree that has focused on the provision of educational institutions for primary and secondary basic education. Also the Decree 1953 (Colombia, Presidencia de la República, 2014) which articulates the proper administration of the Ancestral Territories and which aims to focus on early education, early childhood or awakening of the seeds of life; the Decree 1811 (Congreso de Colombia, 2017) with which the financing of the processes of out-of-school education or needs of the community, such as training young people, arts, the indigenous guard, processes that from school cannot be answered. This regulation allows consolidating local, zonal and regional structures to achieve self-emancipation in the own educational system from financial autonomy, in the development and pedagogical experiences and in guiding and directing own education.

There are great advances, but it is not yet possible to consolidate that their own education can be applied in a collective education. It is necessary to know the ethnic and cultural complexity of Colombia and Latin America that requires overcoming unifying and homogenizing educational approaches (Rojas-Curieux, 2019). One possible path is to generate educational processes focused on these ethnic minorities which lays the foundation for creating a collective consciousness that allows inclusion and knowledge of all the different cultures that exist in a nation (Osorio-Mejía and Lozano-Céspedes, 2019). This will allow the affirmation of the constitutional rights of this population; hence it fits pedagogically and legislatively to the multiethnic and multicultural context of the country, in the so-called Intercultural Bilingual Education, which, in Colombia, is the so-called education for cultural diversity or ethno-education, which is defined as the space for a different type of education.

These laws strengthen the language and ways of life of indigenous peoples, allowing their dignity, freedom and equality in rights (Sánchez-Moreno and Escalera-Silva, 2021). However, these policies

are based on universal anthropological principles that propose education as the path to achieve social progress and ethnic inclusion in a country (Ruiz-Cabezas and Medina-Rivilla, 2014). In this sense, ethnic communities, originally from the territory, relate the concept of Sustainable Development (Brundtland, 1987) from traditions and worldviews (Cuervo-González, 2017); i.e., from the irradiation of ancestral knowledge, ancestral and vernacular practices, culture and preservation experiences of biodiversity of their territories for future generations and whole humanity (Chen and Gilmore, 2015; García-Parra et al., 2022).

For integrating it, it is necessary that teachers and ethno-educators have knowledge, competences, values and attitudes to perform this task, are focused on the improvement of society, the economy and the environment from interactive ethnopedagogies that achieve sustainable projects for life. Tobón et al. (2018) analyze pedagogical practices from conceptual cartography. This perspective allows generating actions towards sustainable social development from the knowledge society, since the formation of communities allows finding solutions to the problems of the context and the territory, thus providing real and better living conditions of people. Acevedo-Osorio et al. (2020) relate the preservation of agro-systems and biodiversity as a strategy of family agriculture. This allows to adapt and respond to the problems and impositions that support their production structures, becoming the definitive component of ethnoeducational processes versus the defined as sustainability, improving the well-being conditions of the communities in their territory (Castro-Castro et al., 2021).

Another case is presented by Peralta et al. (2019), who propose an ethno-education model for the Mokaná community of Malambo, Colombia. This *model* has as its root to preserve ancestral languages, traditions and practices for the new generations. Therefore, it is necessary to promote a more complete and excellent education, where all students can contribute to sustainability from the socio-training (Merlo, 2020). They must also learn by self-motivation, looking for solutions to conflicts and leaving aside traditional education based on subjects, which affects creativity and entrepreneurship (Tobón et al., 2018).

For this reason, students must also appropriate a whole context offered by teachers in which they are provided with the tools to have a proper criterion of equity, tolerance, social justice, preservation, restoration, and conservation of natural resources to transcend in time with better conditions of social development and welfare of communities. In conclusion, the educational proposal of the Colombian State has considered the incorporation of own knowledge, nor the contributions of other members to the teachers in charge of teaching it.

According to the above, the aim of this paper is to conduct a bibliometric exploration of the advances of scientific studies in ethnoeducation, ethnopedagogy and its contribution to the promotion of sustainable development supported by Scientometric tools, answering if ethnoeducation contributes to the promotion of sustainable development from the act of pedagogy in First Peoples.

2 Research Methodology

The work is carried out from the qualitative paradigm (Strauss and Corbin, 2016) and quantitative (Díez-Gómez et al., 2019); it is descriptive, exploratory, non-experimental, simple and interpretative cross-section, since an interpretation of the scientific documents analyzed is made to generate categories of study from the mixed systematic review method (Oraee et al., 2017). Therefore, a description of the eligibility criteria, research and search sources, as well as the process of study selection, data extraction and synthesis of results found in the indexes of *Scopus, Web of Science* and *Dimensions* databases were collected, which allowed selecting the most relevant scientific documents against the related subtopics of ethno-education, ethno-pedagogy and sustainable development.

In the process, bibliometric techniques were used, supported in *Bibliometrix* (Aria and Cuccurullo, 2017), *Tree of Science [ToS]* (Zuluaga et al., 2022; Robledo et al., 2022), analysis of knowledge networks through *Gephi* (Zuluaga-Rojas et al., 2016; Blondel et al., 2008), text mining from *VOSviewer* (Van Eck and Waltman, 2020) *WordCloud* (Fellows, 2018) and review log (Semanate-Quiñonez et al., 2022). Figure 1 presents the methodologically defined moments, the tools used and the products of

this study.

2.1 Moment I: Search Process

As a first step, a bibliometric analysis of the research topic of scientific production found on *Scopus, Web of Science* and *Dimensions* from 2017 to 2021 was performed; sources consulted on December 2021 followed the selection criteria: year, most cited and topic. The research areas through which the results were filtered were *Education or Studies in Human Society or Sociology or Curriculum and Pedagogy or Cultural Studies or Specialist Studies in Education or Language, Communication and Culture, Ethnic Studies, Social Sciences Interdisciplinary, Education Educational Research*. The *Dimensions* database was filtered by the Sustainable Development Goals: *4 Quality Education* or *10 Reduced Inequalities* or *1 No Poverty*. Item Type: *Bronze or Hybrid or Green or Gold or All OA*. This showed the advances and research trends of the subject studied, systematized information in the instrument designed by Semanate-Quiñonez et al. (2022).

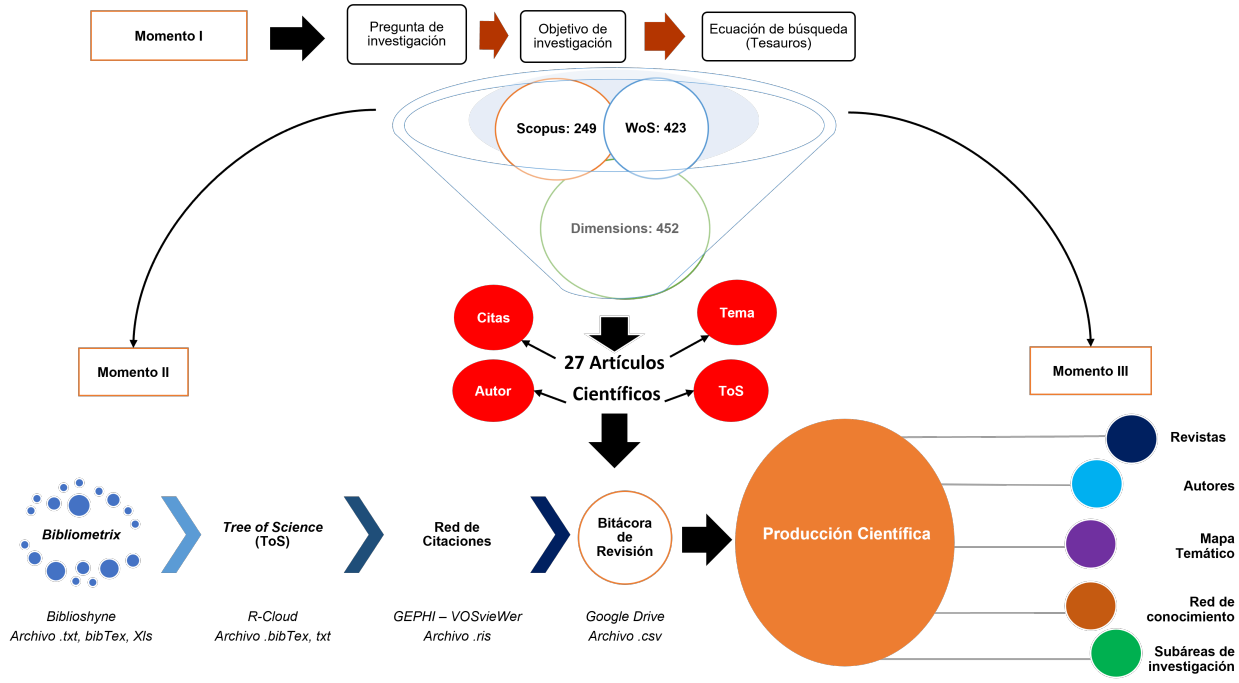

Figure 1. Figure inspired in the prism method (Sánchez-Meca and Botella, 2010) and Burbano-Criollo (2022).

2.2 Moment II: Tree of Science

The results obtained from the previous consultations were analyzed in the *Web Tree of Science (ToS)* tool, categorized as a systematic bibliographic review method with a quantitative approach (Díez-Gómez et al., 2019) and according to Robledo and Duque-Méndez (2017), ToS classifies scientific documents as Root to seminal or classical works; Trunk, structural works that give continuity or foundation to the root; and Leaves, which presents current or emerging works and can be categorized as research trend (Zuluaga-Rojas et al., 2016). Through this method, it was possible to identify the most notable indexed scientific documents related to the areas of ethno-education, ethno-pedagogy and ethnic population, recording their advances and trends of research in sustainable development.

2.3 Moment III: Analysis and interpretation of research subareas

To identify the research subareas, databases were analyzed in the VOSviewer software (Van Eck and Waltman, 2020) and the results were triangu-

lated with the results of the *Tree of Science* generated in *RStudio-Cloud* (Zuluaga-Rojas et al., 2016) to identify the three most significant topics in the research area. The clusterization algorithm applied in the *Gephi* software allowed to obtain the research knowledge network (Blondel et al., 2008). Finally, the databases obtained in *RStudio-Cloud* were analyzed with the *Bibliometrix* package (Aria and Cuccurullo, 2017) which yielded the annual scientific production, the most cited authors, the sources with the greatest citations and the thematic map of research trends to select the articles with greater thematic importance.

3 Research results and discussion

The scientific documents that determined the understanding of the contributions of ethno-pedagogy to sustainable development were selected. Table 1 presents the sources of information, the search equation and the total results found and filtered from the UNESCO (2021) keywords and thesaurus.

Table 1. Review Criteria.

Source of information	Search Equation	Keywords/UNESCO Thesauri	Total
Dimensions	"Education AND pedagogy AND indigenous AND ethnicity"	*Indigenous communities, good living, ethnoeducation. *Ethnic group, pedagogy, bilingual education.	452
Scopus	(Education) AND (pedagogy) AND (indigenous)	*Ethnicity, socioeducation, ethno-education, sustainability, interculturality *Pedagogy, national identity.	249
Web of Science	"Education AND pedagogy AND indigenous"	* Socioformation *Pedagogical practices	423

3.1 Scientometric Results

It was found that the scientific indexing of the analyzed period in the research topic has increased. Most publications are indexed in *Dimensions* with 453 documents, followed by *WoS* with 309 and *Scopus* with 149 scientific documents (see Figure 2).

The analysis carried out with Bibliometrix allowed finding the countries with the greatest number of researches in the topic as it is presented in Figure 3.

Australia ranks first with more than 60 scientific papers, followed by the United States; however, it is worth noting that among the 20 most influential countries there are three South Americans, Mexico ranked seven, Brazil ranked eleven (11) and Chile ranked sixteen (16).

Bibliometrix by means of *RStudio-Cloud* allowed to identify topics of research trend, synthesized in the thematic map of Figure 4. The results show that the most cited topics and authors regarding research topics are pedagogy (Walsh et al., 2018), indigenous knowledge (Zurita-Álava et al., 2017), integrality (Williamson, 2004, 2005); the topics with more centrality and density are placed in the center of the map. In the same order, it is observed a tendency to use the concept of diversity (López, 1997; Zurita-Álava et al., 2017) and inclusive didactics (Colom Cañellas, 1998).

However, to make an analysis of the selected scientific documents, the knowledge network was developed with the authors who contribute significantly to the analysis of the research topic. To achieve this, *RStudio-Cloud* generated the "targets

and sources" to then obtain the graph in the *Gephi* software (Darko et al., 2019; Dervi ş, 2019) and edit it in the following Figure 5.

ToS also served as a reference for the identification and analysis of concepts, thus allowing the visualization of pedagogical and intercultural views influenced by ancestral legacies of their worldviews. Table 2 of the annex summarizes the Tree of Science generated by ToS in the *RStudio Cloud* web tool, categorized by subject area and total citations of the works. *ToS* threw nine (9) scientific papers root, seminal, among which stand out Tuck and Wayne Yang (2012), who work with decolonization and indigenous life; Nakata (0007) with education and analysis of native students in the processes of formal education to decolonize indigenous studies and pedagogical approach. Ten (10) stem scientific documents, structural and root connectors. Among the most cited authors are Ladson-Billings (1995) who works on pedagogical research, improving education and collaborative and reflective research; Gruenewald (2003) with critical pedagogy and place-based education, human relations, decolonization and reintegration and Wolfe (2006) with colonialism of settlers and the elimination of natives.

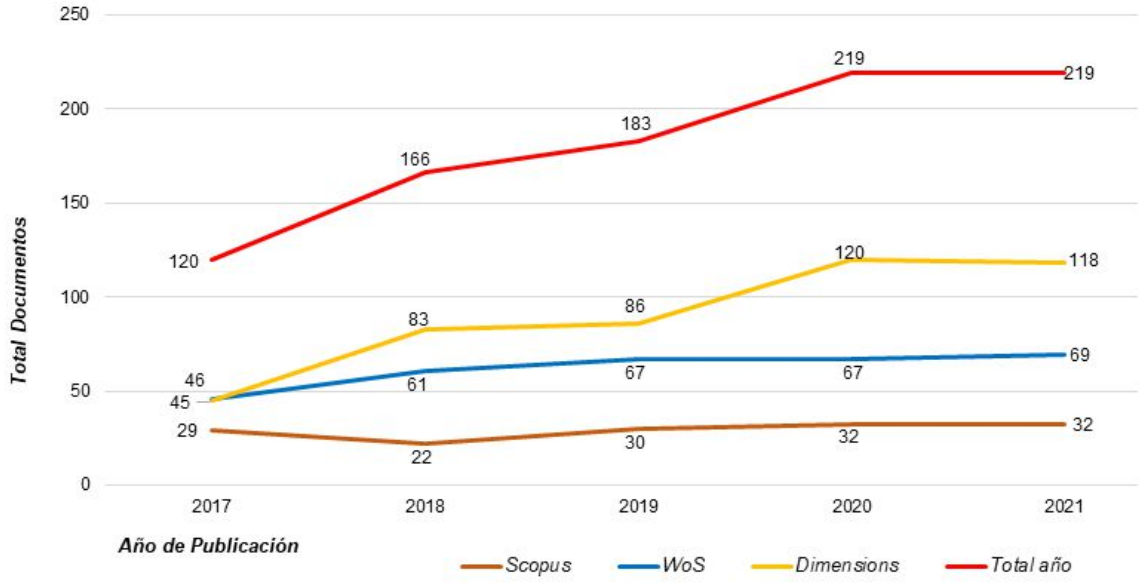

Figure 2. Annual scientific output by total published works.

McCarty (2014) address the critical pedagogy of culture-based indigenous support and education. Sutherland and Swayze (2012) with scientific education in indigenous environments and the importance of place in the indigenous context, as well as Madden (2015), who works on pedagogy for decolonization, indigenous education and anti-racism based on place. Ten (10) scientific documents categorized as Leaves or research trend and / or emerging is Harrison (2020) and Dreamson (2018, 2016) who work on indigenous pedagogical cultures, intercultural education and cultural diversity. Higgins (2014) with decolonized theory, knowledge and ways of being indigenous, which opens new paradigms of education and linguistic models (Hino, 2018, 2020). Burgess et al. (2020) contribute about the professional learning of teachers since the decolonization of indigenous education.

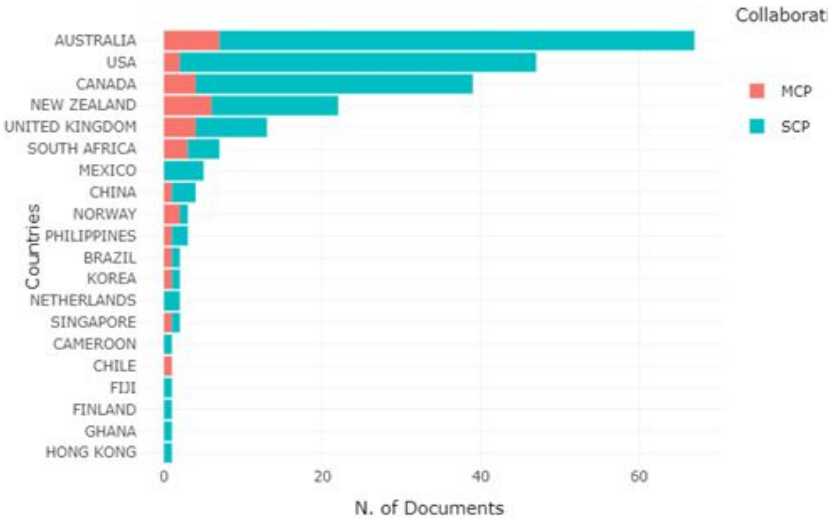

Figure 3. Scientific production by country.

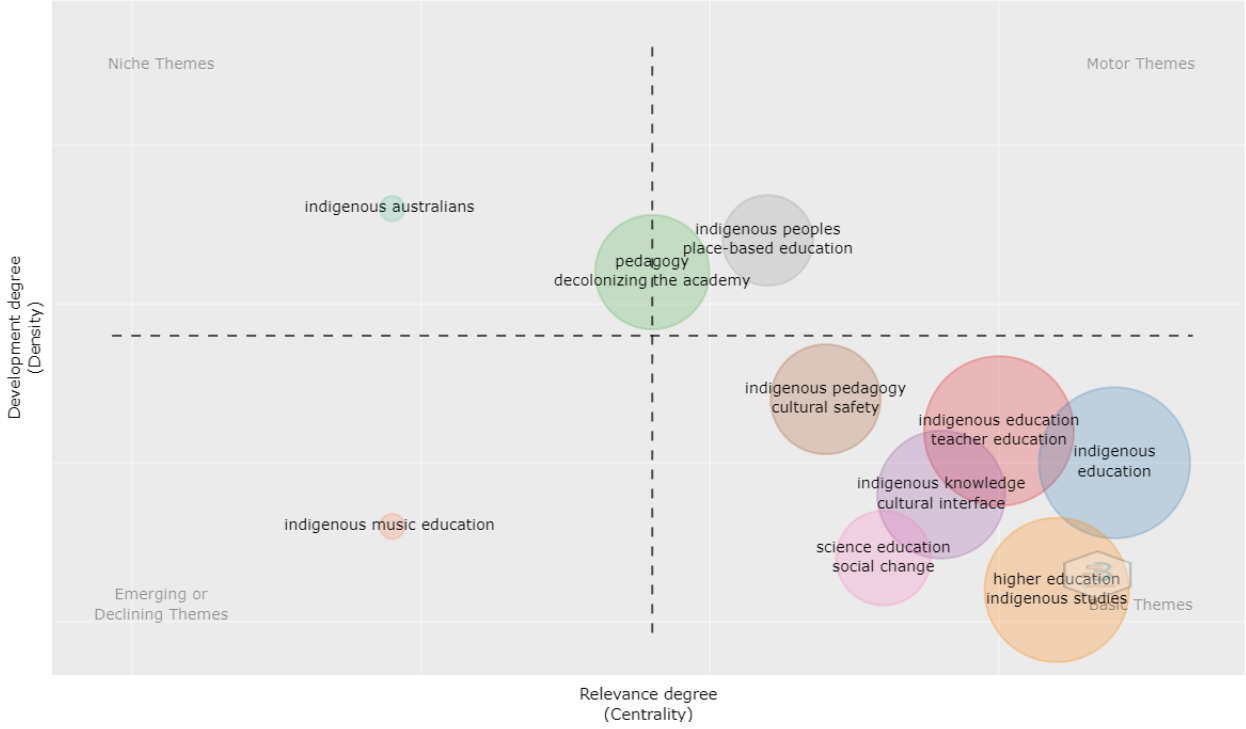

Figure 4. Results released by *biblioshiny* for Bibliometrix on January 2022. Density refers to the correlation of topics; while the Centrality refers to the frequency of citations.

Scully (2020) in the face of the common knowledge of teachers, peoples, lands and histories for indigenous education, and Sosa-Provencio et al. (2019) analyze entrenched pedagogy for the construction of critical awareness and pedagogies that support, involve and improve the educational out-

comes of aboriginal students Burgess et al. (2019). Finally, in order to identify clusters and research trends, the databases were processed in the *VOSviewer* software, which allows making a normalization analysis with the fractionation method from the number of occurrences per topic and year of publication. Figure 6 presents the subareas of greater research concentration defined by education, pedagogy and knowledge in the face of sustainable development, which can direct the dissertation from the selected authors.

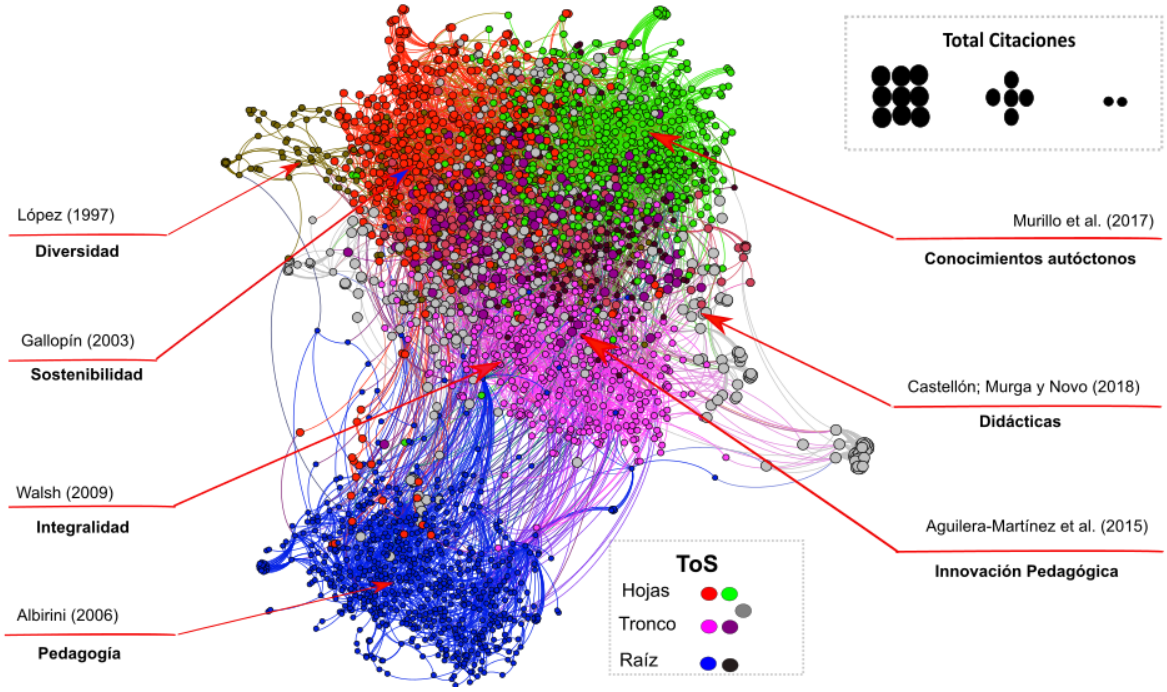

Figure 5. Knowledge Network.

3.2 Results of research sub-areas

In order to highlight the main topics of trend and relevance to the research, reference is made to:

- Pedagogy: The author with the highest citation rate in this topic is Albirini (2006), who worked on teachers' attitudes towards the use of ICTs to revolutionize the educational system.
- Pedagogical Innovation: Aguilera-Martínez et al. (2015) contribute to building learning through the experience and imaginaries that students project in front of the environment they inhabit.
- Indigenous knowledge: Zurita-Álava et al. (2017) work on cultural knowledge in the raising of children.
- Walsh (2009), analyzes critical interculturality and de-colonial pedagogy; bets of the in-emergence, re-existing and re-live Cuello Ramírez and Garrido Serpa (2020).
- Diversity: the most significant author in this topic is López (1997), who addresses the problems and challenges of rural education in Colombia.
- Didactics: Castellón (2018) works on ethnoeducation and intercultural practices; and Murga-Menoyo and Novo (2017) address pedagogy for sustainable development.
- Sustainable Development (SD): Sustainability and SD are seen from different approaches, do not mean the same and do not have the same approach. Sustainable development is part

of the idea of generating a progressive change, while sustainability is the process of improving the quality of life of people (Gallopín, 2003).

- Ethno-education: allows us to analyze the thoughts and practices in the different ethnic communities, the historical process and the cultures of the First Peoples in the territory. It also allows incorporating the community pedagogical discourse, which disagrees with current globalizing and modernist tendencies originated from the structural-colonial-racial, which has forged the loss of cultural identity, beliefs and language of ethnic communities (Acevedo, 2019).
- Culture: Mora (2013) reflects epistemologically on culture from human experience in nature, evolutionary stagnation and understanding as a system. Culture contributes to defining the Environmental Dimension, advancing the concept of Environmental Sustainability of Development and deepening Sustainable Development as an integral commitment of each Nation and States.

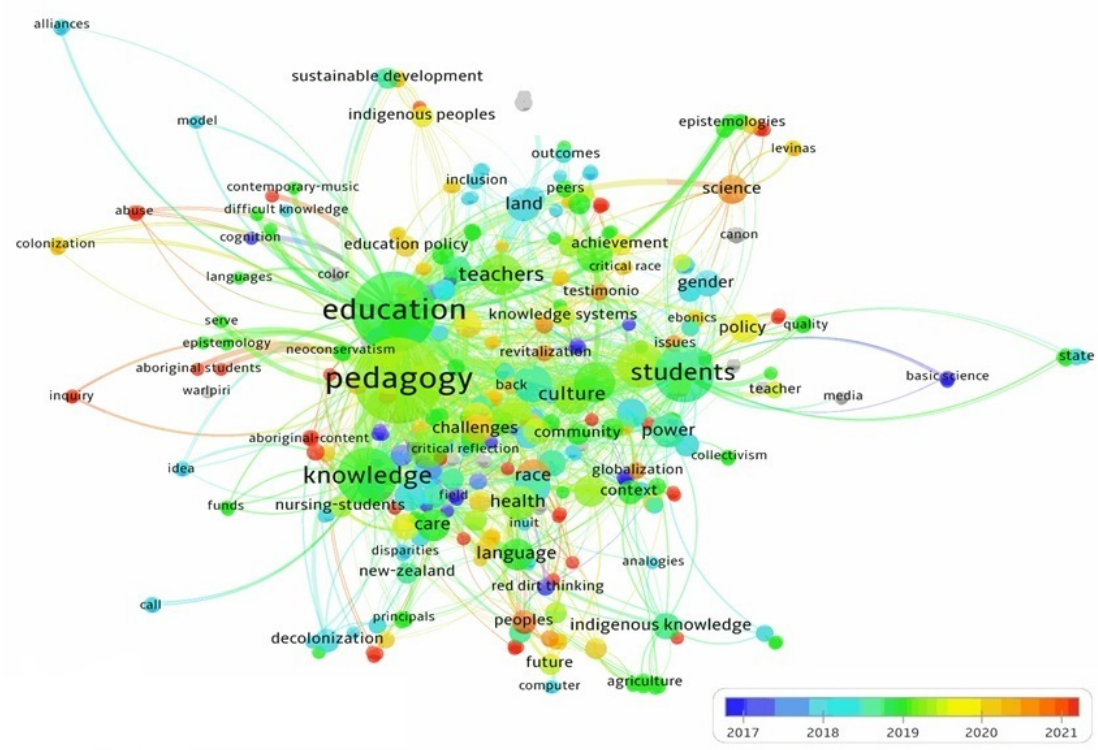

Figure 6. Sub-areas of research. Figure homemade with *VOSviewer* software.

4 Ethno-education and Ethno-pedagogies for Sustainable Development (SD)

Sustainability

The pedagogy for sustainability emphasizes the responsibility of humanity towards Mother Earth, nature and Territories, which is necessary to achieve social equity between individuals (Murga-Menoyo and Novo, 2017). To achieve this, in addition to the growth of a nation, it is essential to have pedagogical bases which are applicable in the day-to-day of each person. Therefore, it is necessary to improve the pedagogical process with emphasis on sustainability, planetary citizenship and glocality. The complexity of the process is to adapt and articula-

te all humanity with nature in a planetary model that generates a glocal development coupled to the approaches of sustainability (Murga-Menoyo and Novo, 2017).

However, from the ethno-educational proposals offered by indigenous cultures, these allow identifying the visions and imaginaries of their communities to create and value the world. Ethno-education assumes some principles of the Good Living (Capitán et al., 2019) and environmental education (Vásquez, 2020), such as the importance of rebuilding ancestral knowledge, which are rejected by Western logics, stressing the need to hybridize them with current knowledge, coinciding with the Community Model of Sustainable Development, which would allow finding innovative strategies to solve the current decline of humanity (Martínez et al., 2016).

Therefore, there is no clear definition of the SD for ethnic communities and First Peoples within a reference framework of important concepts that encompasses the definition, so it is assumed the one by Martínez et al. (2016) of "indigenous community sustainability", which articulates three important approaches: 1) Sustainable Lifestyles, 2) Community Model of Sustainable Development, and 3) Good Living, which correlate and modulate the dimensions of the SD "ecological, social, cultural, economic and political", pillars of First Peoples.

This leads to create a conceptual synthesis from the communities and forms to integrate the concept of sustainability to the territories from recovery actions and rehabilitation of ecosystems, sustainable use and use of environmental goods and services (Mora, 2013).

This is how sustainability can be defined from ethno-education as the process that allows the valuation, preservation and transmission of ancestral knowledge from the appropriate management of the natural resources that exist in the territory and conservation for future generations; this occurs from ethno-pedagogical methods that allow the harmonization of the territory, food sovereignty and security, the recovery of traditional productive practices and a sustainable and equitable regional economic exchange [from the perspective of the First Peoples]. This is how ethno-education for sustainability is conceived from the People's Assemblies and the participation of its members in projects, in addition to the harmonious integration of its ancestral practices with current ones (Martínez et al., 2016).

As a conclusion, ethno-pedagogy is the process of life itself, since teaching not only focuses on educating oneself in something for work performance but is also essential to understand and learn to value the planet, the family, and even life itself; all this is a learning that could be called the pedagogy of life with constant learning method to achieve sustainability.

Education and Interculturality

The First Peoples are the most important minority that preserves the reality of the ancestors before being a nation colonized by different cultures. Intercultural education makes it possible to integrate learning processes into the cultural and historical environment, hence it is important to consider all the diversity that exists in the territories; we cannot speak of plural democratic pedagogy just because most are the ones who make the difference.

So, who should the school educate? Castellón (2018) analyze the question raised from antiquity to the present day, in search of a logical and concrete answer that can determine this enigma focused on the central axis of politics.

The answer to the question is that modernity has injected the school with a way of learning to modern society, where it is sought that citizens are educated in a system of thought and behavior where the purpose and interest is recognized by the majority in a democratic way; however, by giving continuity to this model, minorities will never be taken into account and their rights will always be violated. Therefore, the modern State must propose projects for the formation of citizenship. These must be managed from the societies and managed correctly, where civic education is a priority to improve and include in the State policies and Development Plans the component of own education and ethno-pedagogical of the different cultures existing in the nation and not directed by a dominant political project (Sánchez-Otero et al., 2019).

Ethno-education and curriculum

Regarding the implementation of ethno-education from educational policies, "currents of reflection and innovation have been generated, leading to a substantial modification of educational practice" (Ruiz-Cabezas and Medina-Rivilla, 2014, p. 6). This, according to Moreno and Silva (2021), has managed to condemn the different grounds of discrimination and provide the right of political participation for the construction of educational regulations of the State concerning ethnic populations, thus providing the enjoyment of collective and individual human rights.

Thus, the aim of ethno-education is to achieve the integration and transversality of the curriculum of the Western school versus knowledge (Nakata, 2011). For this reason, it is essential to think about another form of school, one that allows life, the valuation of ancestral knowledge from the recovery of practices, and knowledge, since education offers with other values different from those of the First Peoples, separated from the moments of life of the communities.

Through the study of the academic curriculum and the foundation of its own structures, it has been possible to strengthen the forms of ethno-education. Not the curriculum as it is known or called, since this would mean adapting the foreign, leaving outside fundamental areas of knowledge of ethnic communities framed in ancestral knowledge. Therefore, knowledge must be integrated, thought cannot be fragmented or condensed into a curriculum. There must be integration between the territory and society, the community and nature, the mathematics and the production, the communication and the language, the organization and the politics, without leaving the fundamental, the wisdom and the ancestral worldview.

It is also found that the "flexibility" of the programs for ethnic students proposed by Higher Education Institutions (HEI), are assumed as "low quality" and the associativity of "differentiationïs not understood (Mato, 2011). In addition to this, it is necessary to design instruments and procedures particular to the evaluation processes that integrate the holistic view of the ethno-educational, ethno-pedagogical proposals and the contexts in which they are developed, including their teachers, ethno-educators and researchers.

The above implies a tendency of appropriation of ethno-education and ethno-pedagogy in new intercultural and pedagogical spaces that are adapted simultaneously with traditional practices, which allow to affirm cultural identity, generate intercultural dialogues and achieve the encounter with the other (Castellón, 2018).

5 Conclusions

The review allowed to identify the evolution in the challenges of ethno-education in intercultural contexts, where educational processes must end from the matrix of First Peoples and drive a new "development" with traditional practices gestated from educate to be and not adapt it to traditional educational doctrines, thus achieving a conservation of diverse cultures that continue struggling to obtain their own education.

From the results analyzed, it is evident the evolution of topics that integrate the culture, knowledge and practices of the original communities against what is defined as Sustainable Development. Finally, it is possible to resemble the original cultures, which through their language and beliefs achieve a grounded knowledge of research for education of their own culture (ethno-education), focused on methodologies outside the classroom, with an education based on how to orient the learning process from their visions, beliefs and imaginaries.

Author Contributions

Conceptualization, HASQ; data processing, HASQ; formal analysis, HASQ; research, HASQ and CASM; resources, CASM; methodology, HASQ; software, HASQ; visualization, HASQ and CASM; validation, CASM; writing-original draft, HASQ; supervision, CASM; writing-review and editing, CASM.

References

Acevedo, S. (2019). *Educación y buen vivir: hacia una educación superior intercultural: estudio de caso del*

programa licenciatura en etnoeducación de la UNAD. PhD thesis, Uniandes.

Acevedo-Osorio, A., Przychodzka, S., and Pinilla, J. (2020). Contributions of agrobiodiversity to the sustainability of family farming in colombia. *Tropical and Subtropical Agroecosystems*, 23(2):1–18. Online:https://bit.ly/3Lp5dxq.

Aguilera-Martínez, F., Vargas-Niño, P., Serrano-Cruz, N., and Castellanos-Escobar, M. (2015). Estudio de los imaginarios sociales urbanos desde las prácticas pedagógicas. *Revista de Arquitectura (Bogotá)*, 17(1):104–110. Online:https://n9.cl/xvz7r.

Albirini, A. (2006). Teachers' attitudes toward information and communication technologies: The case of syrian efl teachers. *Computers y Education*, 47(4):373–398. Online:https://n9.cl/p7akj3.

Aria, M. and Cuccurullo, C. (2017). bibliometrix: An r-tool for comprehensive science mapping analysis. *Journal of informetrics*, 11(4):959–975. Online:https://n9.cl/m75bc.

Barragán-Varela, L. (2020). Etnoeducación: Los nuevos retos de pensar la educación indígena en colombia. *Revista del CISEN Tramas/Maepova*, 8(1):35–50. Online:https://n9.cl/1pvbs.

Blondel, V., Guillaume, J., Lambiotte, R., and Lefebvre, E. (2008). Fast unfolding of communities in large networks. *Journal of statistical mechanics: theory and experiment*, 2008(10):P10008. Online:https://n9.cl/h2p41.

Brundtland, G. (1987). Informe de la comisión mundial sobre el medio ambiente y el desarrollo: Nuestro futuro común. Technical report, Documentos de las Naciones, Recolección de un Consejo de Administración de Acuerdos Globales. Online:https://bit.ly/34SKLUU.

Burbano-Criollo, C., A.-M. M. . S.-Q. n. H. (2022). La agricultura urbana como alternativa de abastecimiento de alimentos vegetales: un ejercicio desde la cienciometría. *Informador Técnico*, 86(2):254–277. Online:https://doi.org/10.23850/22565035.4427.

Burgess, C., Bishop, M., and Lowe, K. (2020). Decolonising indigenous education: the case for cultural mentoring in supporting indigenous knowledge reproduction. *Discourse: Studies in the Cultural Politics of Education*, 43(1):1–14. Online:https://bit.ly/3QgwgOm.

Burgess, C., Tennent, C., Vass, G., Guenther, J., Lowe, K., and Moodie, N. (2019). A systematic review of pedagogies that support, engage and improve the educational outcomes of aboriginal students. *The Australian Educational Researcher*, 46:297–318. Online:https://bit.ly/46JCLjP.

Capitán, A., Álvarez, S., Guevara, A., and Carranco, N. (2019). Los objetivos del buen vivir. una propuesta alternativa a los objetivos de desarrollo sostenible. *Revista iberoamericana de estudios de desarrollo= Iberoamerican journal of development studies*, 8(1):6–57. Online:https://bit.ly/3Q7PJjG.

Castellón, E. (2018). Etnoeducación y prácticas interculturales de saberes otros. *Utopía y Praxis Latinoamericana*, 23(83):166–181. Online:https://n9.cl/2u779.

Castro-Castro, M., Beltrán-Díaz, A., and Vargas-Espítia, A. (2021). Análisis sistémico de la sostenibilidad económica de unidades de producción agropecuaria familiar en una comunidad campesina de lebrija, colombia. *La Granja: Revista de Ciencias de la Vida*, 34(2):141–153. Online:https://bit.ly/48BrGT3.

Chen, C. and Gilmore, M. (2015). Biocultural rights: A new paradigm for protecting natural and cultural resources of indigenous communities. *International Indigenous Policy Journal*, 6(3):1–17. Online:https://bit.ly/3O7LqDM.

Colom Cañellas, A. J. (1998). El desarrollo sostenible y la educación para el desarrollo. *Pedagogía social: revista interuniversitaria*, (2):38–50. Online:https://bit.ly/3HHn5Bp.

Colombia, Presidencia de la República (2010). Decreto no. 2500 de julio 12 de 2010. Online:https://bit.ly/3NkTjUZ.

Colombia, Presidencia de la República (2014). Decreto 1953 de 2014. Online:https://bit.ly/3yjLlHu .

Congreso de Colombia (1994). Ley 115 de febrero 8 de 1994. por la cual se expide la ley general de educación. Online:https://bit.ly/3OK54pe.

Congreso de Colombia (2017). Decreto 1811 de 2017. Online:https://bit.ly/3NlxUeb.

Cuello Ramírez, H. and Garrido Serpa, N. (2020). Un análisis estructural y pedagógico al problema del reconocimiento étnico desde la interculturalidad en la institución educativa álvaro ulcue chocue. Master's thesis, Institución Universitaria Politécnico Grancolombiano.

Cuervo-González, L. (2017). *Un análisis estructural y pedagógico al problema del reconocimiento étnico desde la interculturalidad en la Institución Educativa Álvaro Ulcue Chocue*. CEPAL -Naciones Unidas.

Darko, A., Chan, A., Huo, X., and Owusu-Manu, D. (2019). A scientometric analysis and visualization of global green building research. *Building and Environment*, 149:501–511. Online:https://n9.cl/ykcdt.

Dervi ş, H. (2019). Bibliometric analysis using bibliometrix an r package. *Journal of Scientometric Research*, 8(3):156–160. Online:https://bit.ly/3u4o9wX.

Díez-Gómez, D., Guillén, M., and Rodríguez, M. (2019). Revisión de la literatura sobre la toma de decisiones éticas en organizaciones. *Información tecnológica*, 30(3):25–38. Online:https://n9.cl/t0sq1.

Dreamson, N. (2016). *Reinventing Intercultural Education. A metaphysical manifest for rethinking cultural diversity*. Routledge Press.

Dreamson, N. (2018). *Pedagogical Alliances between Indigenous and Non-Dualistic Cultures. Meta-Cultural Education*. Routledge Press.

Fellows, I. (2018). Package "wordcloud". disponible en https://bit.ly/3CbyB7s. FAOSTAT . Online:https://bit.ly/3CbyB7s.

Gallopín, G. (2003). *Sostenibilidad y desarrollo sostenible: un enfoque sistémico*. CEPAL - Naciones Unidas.

García-Parra, M., De la Barrera, F., Plazas-Leguizamón, N., Colmenares-Cruz, A., Cancimance, A., and Soler-Fonseca, D. (2022). Los objetivos de desarrollo sostenible en américa: Panorama. *La Granja: Revista de Ciencias de la Vida*, 36(2):45–59. Online:https://bit.ly/4aUrvUx.

Harrison, N. (2020). Country as pedagogical: enacting an australian foundation for culturally responsive pedagogy. *Journal of Curriculum Studies*, 52(1):15–26. Online:https://bit.ly/3SaHC9q.

Higgins, M. (2014). De/colonizing pedagogy and pedagogue: Science education through participatory and reflexive videography. *Canadian Journal of Science, Mathematics and Technology Education*, 14(2):154–171. Online:https://bit.ly/46McTno.

Hino, N. (2018). *EIL Education for the Expanding Circle. A Japanese Model*. Routledge Press.

Hino, N. (2020). *ELF Education for the Japanese Context*, pages 27–45. Springer International Publishing.

Ladson-Billings, G. (1995). Toward a theory of culturally relevant pedagogy. *American Educational Research Journal*, 32:465–491. Online:https://bit.ly/3MhCLPP.

López, L. (1997). La diversidad étnica, cultural y lingüística latinoamericana y los recursos humanos que la educación requiere. *Revista Iberoamericana de Educación*, 13(1):47–58. Online:https://bit.ly/3MhwCDf.

Madden, B. (2015). Pedagogical pathways for indigenous education with/in teacher education. *Teaching and Teacher Education*, 51:1–15. Online:https://bit.ly/4778LhO.

Martínez, D., Almada, J., and Espejel, I. (2016). ¿ sustentabilidad comunitaria indígena? un modelo integral. *Sociedad y Ambiente*, (11):4–22. Online:https://n9.cl/ydhjw.

Mato, D. (2011). Universidades indígenas de américa latina: logros, problemas y desafíos. *Revista Andaluza de Antropología*, (1):63–854–22. Online:https://n9.cl/j5vrr.

McCarty, T. (2014). Critical culturally sustaining/revitalizing pedagogy and indigenous education sovereignty. *Harvard Educational Review*, 84(1):101–124. Online:https://bit.ly/3FSrlid.

Mendoza-Castro, C. (2010). La educación indígena ika, kankuama, nasa, wayúu y mokaná fortalecen la interculturalidad en colombia. *Educación y humanismo*, 12(19):148–176. Online:https://n9.cl/at7xt.

Merlo, M. (2020). Gestión del conocimiento desde el enfoque socioformativo hacia el desarrollo social sostenible. *Ecocience International Journal*, 2(2):10–18. Online:https://n9.cl/11ph9.

Molina, C. (2012). La autonomía educativa indígena en colombia. *Vniversitas*, 124(1):261–292. Online:https://bit.ly/3FFT6u1.

Mora, L. (2013). Dimensión ambiental, desarrollo sostenible y sostenibilidad ambiental del desarrollo. In *Eleventh LACCEI Latin American and Caribbean Conference for Engineering and Technology (LACCEI'2013)"Innovation in Engineering, Technology and Education for Competitiveness and Prosperity" August*, pages 14–16.

Moreno, K. and Silva, L. (2021). La protección jurídica de la soberanía alimentaria de los pueblos indígenas. *Ciencia Latina Revista Científica Multidisciplinar*, 5(1):1–14. Online:https://n9.cl/fxb6e.

Murga-Menoyo, M. and Novo, M. (2017). Sostenibilidad, desarrollo glocal y ciudadanía planetaria: referentes de una pedagogía para el desarrollo sostenible. *Revista Interuniversitaria*, (29):55–78. Online:https://n9.cl/8fuoyg.

Nakata, M. (20007). *Disciplining the Savages: Savaging the Disciplines*. Canberra: Aboriginal Studies Press.

Nakata, M. (2011). Pathways for indigenous education in the australian curriculum framework. *The Australian Journal of Indigenous Education*, 40:1–8. Online:https://n9.cl/8fgi0.

Oraee, M., Hosseini, M., Papadonikolaki, E., Palliyaguru, R., and Arashpour, M. (2017). Collaboration in bim-based construction networks: A bibliometric-qualitative literature review. *International Journal of Project Management*, 35(7):1288–1301. Online:https://n9.cl/k9wwg.

Osorio-Mejía, M. and Lozano-Céspedes, J. (2019). Prácticas educativas, identidad cultural y concepciones de lo indígena en colombia: entre la etnoeducación, la interculturalidad y la educación propia. Master's thesis, Pontificia Universidad Javeriana.

Peralta, P., Cervantes, V., Olivares, A., and Ochoa, J. (2019). Educación propia de la etnia mokaná: Experiencia organizacional contemporánea. 25(3):88–100. Online:https://n9.cl/ezpbj.

Robledo, S. and Duque-Méndez, N. (2017). Marketing emprendedor: una perspectiva cronologica utilizando tree of science. *Revista Civilizar de Empresa y Economía*, 7(13):113–123. Online:https://n9.cl/tedyi.

Robledo, S., Zuluaga, M., Valencia-Hernandez, L., Arbelaez-Echeverri, O., Duque, P., and Alzate-Cardona, J. (2022). Tree of science with scopus: A shiny application. *Issues in Science and Technology Librarianship*, (100):Online:https://n9.cl/86c8s.

Rojas-Curieux, T. (2019). Una mirada a los procesos en torno a la educación con los pueblos indígenas en colombia. *Voces y silencios. Revista Latinoamericana de Educación*, 10(1):9–34. Online:https://n9.cl/w1y2b9.

Ruiz-Cabezas, A. and Medina-Rivilla, A. (2014). Modelo didáctico intercultural en el contexto afrocolombiano: la etnoeducación y la cátedra de estudios afrocolombianos. *Indivisa. Boletín de Estudios e Investigación*, (14):6–29. Online:https://n9.cl/8usb6.

Sánchez-Meca, J. and Botella, J. (2010). Revisiones sistemáticas y meta-análisis: Herramientas para la práctica profesional. *Papeles del Psicólogo*, 31(1):7–17. Online:https://bit.ly/3QoeOI4.

Sánchez-Moreno, K. and Escalera-Silva, L. (2021). La protección jurídica de la soberanía alimentaria de los pueblos indígenas. *Ciencia Latina Revista Científica Multidisciplinar*, 5(1):1–14. Online:https://n9.cl/imio4.

Sánchez-Otero, M., García-Guiliany, J., Steffens-Sanabria, E., and Palma, H. (2019). Estrategias pedagógicas en procesos de enseñanza y aprendizaje en la educación superior incluyendo tecnologías de la información y las comunicaciones. *Información tecnológica*, 30(3):277–286. Online:https://n9.cl/pons0.

Scully, A. (2020). Educación basada en la tierra y el lugar crítico en la preparación de maestros canadienses: pedagogías complementarias para el complejo. *Investigación pedagógica*, page Online:https://bit.ly/3a0YnQG.

Semanate-Quiñonez, H., Upegui-Valencia, A., and Upequi-Valencia, M. (2022). Blended learning, avances y tendencias en la educación superior: una aproximación a la literatura. *Informador Técnico*, 86(1):46–68. Online:https://n9.cl/6swdg.

Sosa-Provencio, M., Sheahan, A., Desai, S., and Secatero, S. (2019). Tenets of body-soul rooted pedagogy: teaching for critical consciousness, nourished resistance, and healing. *Critical Studies in Education*, 61(3):345–362. Online:https://bit.ly/3Mjz24x.

Strauss, A. and Corbin, J. (2016). *Bases de la investigación cualitativa: técnicas y procedimientos para desarrollar la teoría fundamental*. Centro Internacional de Agricultura Tropical (CIAT).

Sutherland, D. J. S. and Swayze, N. (2012). Including indigenous knowledges and pedagogies in science-based environmental education programs. *Canadian Journal of Environmental Education*, 17:80–96. Online:https://bit.ly/3FA5o78.

Tobón, S., Martínez, J., Valdez, E., and Quiriz, T. (2018). Prácticas pedagógicas: Análisis mediante la cartografía conceptual. *Revista Espacios*, 39(53):Online:https://bit.ly/3a3CiRy.

Tuck, E. and Wayne Yang, K. (2012). Decolonization is not a metaphor. *Decolonization: Indigeneity, Education & Society*, 1(1):1–40. Online:https://bit.ly/46MVhYP.

UNESCO (2021). Tesauro. online:https://bit.ly/3NuXHAL. UNESCO . Online:https://bit.ly/3NuXHAL.

Van Eck, N. and Waltman, L. (2020). Vosviewer, software y manual. VOSviewer . Online:https://n9.cl/iszjf.

Vásquez, N. (2020). *Educación ambiental de docentes en formación a partir de una propuesta curricular alternativa soportada en la interdisciplinariedad y la responsabilidad ética, política y social*. PhD thesis, Universidad Surcolombiana.

Vitonás, A. (2010). El pebi, 39 años de construcción de una educación propia en colombia. *Revista Guatemalteca de Educación*, 2(3):261–292. Online:https://bit.ly/3FFT6u1.

Walsh, C. (2009). Interculturalidad crítica y educación intercultural. In *Instituto Internacional de Integración del Convenio Andrés Bello (Coordinación), Seminario "Interculturalidad y Educación Intercultural"*.

Walsh, C., de Oliveira, L., and Candau, V. (2018). Colonialidade e pedagogia decolonial: Para pensar uma educação outra. *Education Policy Analysis Archives*, 26:83–83. Online:https://n9.cl/w0hct.

Williamson, G. (2004). ¿educación multicultural, educación intercultural bilingüe, educación indígena o educación intercultural? *Cuadernos interculturales*, 2(3):23–34. Online:https://bit.ly/3ubyh4c .

Williamson, G. (2005). *Estudio sobre la educación para la población rural en Chile*. Universidad Alberto Hurtado.

Wolfe, P. (2006). Settler colonialism and the elimination of the native. *Journal of Genocide Research*, 8(4):387–409. Online:https://bit.ly/3Sguvnk.

Zuluaga, M., Robledo, S., Arbelaez-Echeverri, O., Osorio-Zuluaga, G., and Duque-Méndez, N. (2022). Tree of science-tos: A web-based tool for scientific literature recommendation. search less, research more! *Issues in Science and Technology Librarianship*, (100):1–10. Online:https://n9.cl/p8jft.

Zuluaga-Rojas, M., Robledo-Giraldo, S., Osorio-Zuluaga, G., Yathe, L., González, D., and Taborda, G. (2016). Metabolomics and pesticides: systematic literature review using graph theory for analysis of references. *Nova*, 14(25):121–138. Online:https://bit.ly/3sbzRp5.

Zurita-Álava, S., Murillo-Calderón, F., and Defaz-Gallardo, Y. (2017). Los saberes culturales en la crianza de los hijos. *Revista boletín redipe*, 6(6):97–106. Online:https://n9.cl/h5q24.

Appendix

Table 2. Tree of Science *(ToS)*.

ToS	Title	Total Citations	Topic
Root	Tuck, E., & Yang, K. W. (2012). Decolonization is not a metaphor. Decolonization: Indigeneity, education & society. Available at <https://doi.org/10.1080/13504622.2013.877708>	4650	Decolonization
Root	Nakata, M. (2010). La interfaz cultural. La revista australiana de educación indígena. Available at <https://doi.org/10.34236/rpie.v2i2.8>	761	Indigenous pedagogical research
Root	Ladson-Billings, G. (1995). Toward a theory of culturally relevant pedagogy. Available at <https://doi.org/10.3102/00028312032003465>	9257	Indigenous pedagogical research
Root	Gruenewald, DA (2003). Lo mejor de ambos mundos: una pedagogía crítica del lugar. Available at <https://doi.org/10.3102/0013189X032004003>	2705	Critical Pedagogy
Root	Nakata, M., Nakata, V., Keech, S. y Bolt, R. (2012). Metas descoloniales y pedagogías para los estudios indígenas. Descolonización: indigeneidad, educación y sociedad. Available at <https://bit.ly/3Q80JNI>	336	Decolonization
Root	Castagno, AE y Brayboy, BMJ (2008). Escolarización culturalmente receptiva para jóvenes indígenas: una revisión de la literatura. Available at <https://doi.org/10.3102/0034654308323036>	1067	Indigenous education
Root	Martin, K. y Mirraboopa, B. (2003). Formas de conocer, ser y hacer: un marco teórico y métodos para la investigación indígena e indigenista. Available at <https://doi.org/10.1080/14443050309387838>	1160	Indigenous pedagogical research
Root	París, D. (2012). Pedagogía de sostenimiento cultural: un cambio necesario en la postura, la terminología y la práctica. Available at <https://doi.org/10.3102/0013189X12441244>	2966	Indigenous pedagogical research
Root	Wolfe, P. (2006). Colonialismo de colonos y eliminación de los nativos. Available at <https://doi.org/10.1080/14623520601056240 >	4488	Decolonization
Trunk	Bang, M., Curley, L., Kessel, A., Marin, A., Suzukovich III, ES y Strack, G. (2014). Teorías de la rata almizclera, tabaco en las calles y vivir Chicago como tierra indígena. Available at <https://doi.org/10.1080/13504622.2013.865113>	221	Decolonization
Trunk	Madden, B. (2015). Itinerarios pedagógicos para la educación indígena con / en la formación docente. Available at <https://doi.org/10.1016/j.tate.2015.05.005>	101	Indigenous education
Trunk	Marker, M. (2006). Después de la caza de ballenas Makah: conocimiento indígena y límites al discurso multicultural. Available at <https://doi.org/10.1177/0042085906291923>	179	Indigenous knowledge
Trunk	Sutherland, D. y Swayze, N. (2012). La importancia del lugar en la educación científica indígena. Available at <https://doi.org/10.1177/097340820900400110 >	29	Indigenous pedagogical researcha
Trunk	McCarty, T. y Lee, T. (2014). Pedagogía crítica para el sostenimiento, revitalización cultural y la soberanía de la educación indígena. Available at <https://doi.org/10.17763/haer.84.1.q83746nl5pj34216>	596	Indigenous pedagogical research
Trunk	Mackinlay, E. y Barney, K. (2014). Posibilidades desconocidas y desconocidas: aprendizaje transformador, justicia social y pedagogía descolonizadora en los estudios indígenas australianos. Available at <https://doi.org/10.1177/1541344614541170>	81	Decolonization
Trunk	Martin, G., Nakata, V., Nakata, M. y Day, A. (2017). Promover la persistencia de los estudiantes indígenas a través de la docencia en la Interfaz Cultural. Available at <https://doi.org/10.1080/03075079.2015.1083001>	48	Indigenous knowledge

Trunk	Harrison, N. y Skrebneva, I. (2020). El país como pedagógico: promulgación de una base australiana para una pedagogía culturalmente receptiva. Available at <https://doi.org/10.1080/00220272.2019.1641843>	11	Pedagogical research
Trunk	Bishop, R., Berryman, M., Cavanagh, T. y Teddy, L. (2009). Te kotahitanga: abordar las disparidades educativas que enfrentan los estudiantes maoríes en Nueva Zelanda. Available at <https://doi.org/10.1016/j.tate.2009.01.009>	474	Pedagogical research
Trunk	Yunkaporta, T. y McGinty, S. (2009). Recuperación del conocimiento aborigen en la interfaz cultural. Available at <https://doi.org/10.1007/BF03216899>	182	Indigenous knowledge
Leaves	Dreamson, N. (2018). Alianzas pedagógicas entre culturas indígenas y no dualistas: Educación metacultural. Available at <https://doi.org/10.4324/9780429458811>	6	Indigenous pedagogical research
Leaves	Dreamson, N. (2016). Reinventar la educación intercultural: un manifiesto metafísico para repensar la diversidad cultural. Available at <https://Reinventing+Intercultural+Education>	12	Indigenous pedagogical research
Leaves	Burgess, C., Tennent, C., Vass, G., Guenther, J., Lowe, K. y Moodie, N. (2019). Una revisión sistemática de las pedagogías que apoyan involucra y mejoran los resultados educativos de los estudiantes aborígenes. Available at <https://doi.org/10.1007/s13384-019-00315-5>	12	Pedagogical Research
Leaves	Scully, A. (2020). Educación basada en la tierra y el lugar crítico en la preparación de maestros canadienses: pedagogías complementarias para el complejo. Available at <https://bit.ly/3a0YnQG>	6	Indigenous pedagogical research
Leaves	Burgess, C., Bishop, M. y Lowe, K. (2020). Descolonización de la educación indígena: el caso de la tutoría cultural para apoyar la reproducción del conocimiento indígena. Available at <https://doi.org/10.1080/01596306.2020.1774513>	5	Decolonization
Leaves	Weuffen, SL, Cahir, F. y Pickford, AM (2017). La centralidad de los talleres culturales aborígenes y el aprendizaje basado en la experiencia en un curso de formación inicial para profesores: un estudio de caso regional de la Universidad de Victoria. Available at <https://doi.org/10.1080/07294360.2016.1242557>	9	Indigenous pedagogical research
Leaves	Sosa-Provencio, MA, Sheahan, A., Desai, S. y Secatero, S. (2020). Principios de la pedagogía arraigada en el cuerpo y el alma: enseñanza para la conciencia crítica, la resistencia nutrida y la curación. Available at <https://doi.org/10.1080/17508487.2018.1445653>	13	Pedagogical Research
Leaves	Hino, N. (2018). Educación EIL para el círculo en expansión: un modelo japonés. Available at <https://doi.org/10.4324/9781315209449>	28	Pedagogical Research
Leaves	Hino, N. (2020). Educación ELF para el contexto japonés. Disponible en <https://doi.org/10.1007/978-3-030-33288-4_2>	1	Pedagogical Research
Leaves	Higgins, M. (2014). Pedagogía y pedagoga descolonizadora: Educación científica a través de la videografía participativa y reflexiva. Available at <https://doi.org/10.1080/14926156.2014.903321>	35	Decolonization

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Sustainable Development

Willingness to Pay for Urban Solid Waste integral system in Semi-Urban Populations

Disposición a Pagar por un sistema integral de Residuos Sólidos Urbanos en poblaciones semi-urbanas

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Abstract

In Yucatan, the transition from rural to semi-urban communities has occurred mainly in the municipality seats; this transition comes with the problems of waste management. The municipalities oversee the Integral Urban Solid Waste Management (IUSWM); but in recent years, the public-private partnership for waste management has proved to be an effective strategy. There are few studies on the IUSWM in rural or semi-urban areas and the users' willingness to pay, information that would help public policymakers to design adequate plans and programs for its management. Therefore, the purpose of this study is to determine the socioeconomic factors associated with the willingness to pay for the IUSWM of users in semi-urban municipalities of Yucatan. A total of 1,144 interviews were conducted in 6 semi-urban localities in Yucatan, and the data were analyzed using descriptive and inferential statistics with a Tobit regression econometric model. 69.75% of the surveyed users declared that they were willing to pay an average of 17.65 Mexican pesos (0.85 U.S. dollars) for the integral urban solid waste management. The willingness to pay decreases when the Mayan language predominates among the member of the household, and when they have fewer tangible assets and rooms. There are cultural and social factors rooted in solid waste collection, this integrated system may be accompanied by other types of economic incentives to modify consumers' behavior towards something more beneficial for the environment, such as the homes' income.

Keywords: Urban Solid Waste (USW), Semi-rural area, Willingness to Pay (WTP), Tobit model.

Resumen

La transición de lo rural a lo semiurbano en Yucatán ocurre principalmente en las cabeceras municipales, y trae consigo problemas de gestión de los residuos. Las autoridades municipales son las encargadas del Manejo Integral de los Residuos Sólidos Urbanos (MIRSU); pero en últimos años, la asociación entre el sector público y el privado para la gestión de los residuos resulta una estrategia eficaz. Existen pocos estudios sobre el MIRSU en zonas rurales o semiurbanas y la disposición a pagar de los usuarios, información que ayudaría a los creadores de política pública a diseñar planes y programas adecuados para su gestión. Por lo tanto, el objetivo de este estudio es determinar los factores socioeconómicos asociados a la disposición a pagar por el MIRSU de los usuarios de municipios semiurbanos de Yucatán. Se realizaron 1,144 encuestas en 6 localidades semiurbanas de Yucatán, los datos se analizaron mediante estadística descriptiva e inferencial con un modelo econométrico de regresión Tobit. El 69,75% de los usuarios encuestados declararon estar dispuestos a pagar por el manejo integral de los residuos sólidos un monto promedio de 17,65 pesos mexicanos (0,85 dólares estadounidenses). La disposición a pagar disminuye cuando predomina el idioma maya, y mientras menos activos físicos y habitaciones tenga el hogar. Existen elementos culturales y sociales arraigados en la recolección de residuos sólidos, este sistema integral puede ir acompañado de otro tipo de incentivos económicos para modificar el comportamiento de los consumidores hacia algo más beneficioso para el medio ambiente, tal como el ingreso familiar.

Palabras clave: Residuos Sólidos Urbanos (RSU), áreas semi rurales, Disposición a Pagar (DAP), Modelo Tobit.

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1 Introduction

Globally, the problem of Urban Solid Waste (USW) is increasing due to the growth of population and the change in consumption patterns. According to Kaza et al. (2018), 242 million tons of plastic waste are generated worldwide, and 1.6 billion tons of carbon dioxide equivalent (CO_2 equivalent) greenhouse gas emissions were produced from solid waste management in 2016. If there is no improvement in solid waste generation, emissions will increase 62.5% by 2050.

In 2017, Mexico produced 102,895.00 tons of waste daily, from that amount 83.93% were collected, and 78.54% were disposed in final disposal sites, recycling only 9.63% (Secretaría de Medio Ambiente y Recursos Naturales, 2017). Official information (Fig. 1) at a country, state, and local level regarding solid waste generation is scarce and out of date (last official data was registered in 2012). Notwithstanding the preceding, explicit behavior is observed in the country's commitment to economic growth. The increase in average spending on private consumption by families has led to a constant increment in waste and waste generation. Even in times of economic crisis (2009), the generation of urban solid waste continued to escalate, this effect can be attributed to the economic pause generated by the mitigation actions of the COVID-19 pandemic and that now with the economic reopening, could have a more significant effect in terms of pollution.

The USW production is linked to human activities at the household level (Diario Oficial de la Federación, 2003), so its increase is also related to household consumption patterns and population growth. Research can reveal changes in consumption patterns; for instance, a study was conducted on the island of Crete to identify the composition of waste; the results indicated a change in consumption patterns, mainly due to the increase in packaging materials in contrast to the decrease in organic waste (Gidarakos et al., 2006). On the other hand, as the population grows in a region, it is necessary to establish a more organized form of waste management to maintain general health issues (Seadon, 2006).

The proper management in USW levels has not been accomplished yet (Marín García and Quintanilla Jerezano, 2007). Some USW disposed of landfills have a residual value, such as paper, PET, paper board, milk carton, metal, among others. However, when they are not reused or reintegrated into the economy, this value is missed (Taboada-González et al., 2013). The mismanagement of USW can create harmful effects such as soil, air, and water pollution, loss of biodiversity and health risks (Huamaní Montesinos, 2017; Srivastava et al., 2015). The proper management of USW is an issue that impacts the different dimensions of sustainability (da Silva et al., 2019); therefore, it is important that after collecting data about USW in studies, findings are used by the policymakers to develop or improve an adequate Integral Urban Solid Waste Management (IUSWM).

In Mexico, the *General Law for the Prevention and Comprehensive Management of Waste* of 2003 indicates that an IUSWM is a system related to actions to reduce, re-use, and re-cycle the waste produced, as well as their collection, storing, and final disposal, following the objectives of sanitation, restoration, and conservation of the environment. However, the sectors in which solid waste is generated include industrial, governmental, institutional, and health care (Srivastava et al., 2015).

There is not an accurate definition of IUSWM since it changes depending on the country; moreover, IUSWM goes further the final disposal. Tchobanoglous and Kreith (2002) suggest that selecting and applying appropriate management practices, technologies, and programs to accomplish the objectives can be called a system. The advantages of having an IUSWM in a country goes beyond the preservation of the population's health. It also involves the decrease in use of natural resources and pollution from untreated waste discharge; and indirectly, energy savings (Hui et al., 2006).

Nowadays, the problem of solid waste management is also present in urban and semi-urban areas because of the increase of urbanization. For instance, in the rural areas of India, waste is dumped in inappropriate places (roadsides, vacant lands, etc.), which is dangerous to the residents' health from these areas and affects the environment; there is no separation of waste, and although organic waste is fed to animals, changes in consumption patterns have increased the use of plastic materials that are

disposed in landfills (Vij, 2012). In rural areas of Egypt, it has been documented that solid waste is often dumped in drains and canals, open dumps or burned (El-Messery et al., 2009).

In the last decades in Mexico, rural areas have also been transformed from rural to urban and semi-urban due a demographic growth. This transition from rural to urban comes with the USW management problems, as well as the change in consumption habits. The State of Yucatan[1] is not exempt, it has experienced this transformation especially in municipality seats[2], some of which have reached the size of semi-urban areas. Unfortunately, the USW problem is present inside them (like the increasing use of disposable and dangerous materials). It is exacerbated when the communities have no adequate trash collection services. This remains latent in the information reported by Secretaría de Desarrollo Social (2013) (Table 1), where growth in the generation of urban solid waste can be observed in rural or semi-urban areas. The state of Yucatán has also registered increases in the volume of USW generation, obtaining a total of 620 thousand tons for the year 2012.

The only municipality in the state of Yucatan that has a sanitary landfill is Merida, and the other municipalities have lack of proper landfill. As a result, the waste in rural and semi-rural locations is burnt, and dumped in landfills, ground holes, and streets. Among the problems caused by poor management of USW there can be found environmental pollution (air, soil, water, visual), unpleasant odors, rodents and pests, and issues that endanger inhabitants' health (Canul Bacab and May Hoil, 2016). In Yucatán, initiatives have been developed due to USW, an example of these initiatives is that all its municipalities, have a Solid Waste Management Plan (Secretaría de Desarrollo Sustentable, 2021). However, the application of these plans requires investment, innovation, and the link between the social, private, and public sectors to begin having positive effects in reducing USW.

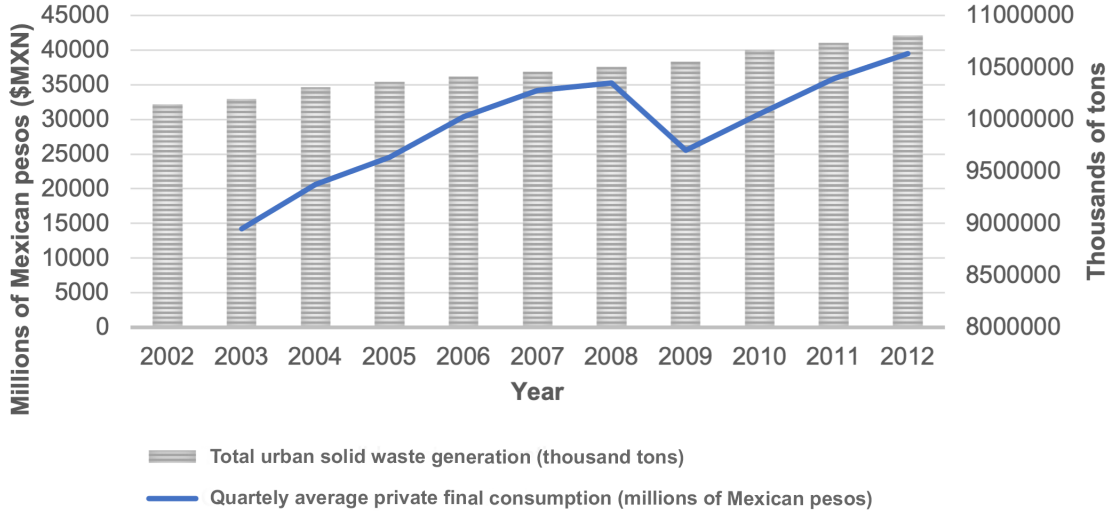

Figure 1. Urban solid waste generation and private consumption in Mexico
Source: Own elaboration based on data from Secretaría de Desarrollo Social (2013).

[1]One of the 32 states of the Mexican Republic.
[2]Also known as *Cabecera municipal* in Spanish. It is a city or town seat of the municipal government. Mexico has three levels of government: Federal, State and Municipal, and 32 States and 2 471 Municipalities.

Table 1. Urban solid waste generation by type area

Year	National urban solid waste generation (thousands of tons)	Urban solid waste generation in Yucatán (thousands of tons)	Solid waste generation in rural or semi-urban locations (thousands of tons)
2002	32 173.60	459.52	4 774.20
2003	32 915.70	470.85	4 793.00
2004	34 604.00	496.00	4 964.00
2005	35 405.00	509.00	5 326.00
2006	36 135.00	522.00	5 088.00
2007	36 865.00	551.00	5 021.00
2008	37 595.00	562.00	4 540.00
2009	38 325.00	573.00	4 561.00
2010	40 058.75	591.30	4 639.50
2011	41 062.50	605.90	4 704.30
2012	42 102.75	620.50	4 726.00

Source: Own elaboration based on data from Secretaría de Desarrollo Social (2013).

In Mexico -according to Article 115 of the Political Constitution- municipalities oversee cleaning, collection, treatment, and final disposal of waste. However, Mexico has experienced a noticeable change in public services, as more and more private services replace them. This includes the potable water supply, street lighting, and waste collection services (Couto Benítez et al., 2012). The participation of private sector has become an alternative solution to the problem of waste management, mainly in urban areas (Couto Benítez et al., 2012). Some studies address the population's willingness to pay for the trash collection system, as well as the factors that influence this decision (Kayamo, 2022; Koford et al., 2012; Song et al., 2016).

The studies on USW management are focused on urban areas which have a large population (in Mexico urban is upper than 15,000, and rural is below 2,500 inhabitants, in between: semi-urban). Nevertheless, these results are not likely to be applicable in semi-urban areas, as they are smaller (Friesen-Pankratz et al., 2011).

Therefore, there is a lack of information on USW collection and final disposal in rural and semi-urban areas, and also about the factors that incentive these inhabitants to acquire a waste collection service (WCS). For that reason, the purpose of this study is to determine the socioeconomic factors associated with the willingness to pay in order to create an integral solid waste management system (ISWMS) in semi-urban cities in Yucatán.

2 Materials and Methods

A quantitative approach with non-experimental design and cross-sectional type was used in this study by analyzing descriptive and inferential statistics through a truncated regression econometric model (Tobit). The data was collected in only one period between January and March 2021.

The design of the study considered having spatial representativeness of the semi-urban cities in municipalities in the state of Yucatan[3], those were selected according to their spatial distribution. The state was divided into six areas, considering the central, the northeast, northwest, southeast, and southwest areas. The municipalities selected according to the criterion of representativeness were: Halacho, Izamal, Muna, Peto, Tekax, and Tizimín, and the semi-urban cities selected inside them are their municipal seats; both are reported in Figure 2: municipality full colored and dot semi-urban city.

The sample size was calculated for each municipality seats with 95% confidence, 10% of error and, the positive response of 90% and negative response

[3] Yucatán has 106 municipalities.

of 10%. A total of 1,144 interviews were collected (Table 2), which were supplied and answered physically and personally (face to face), contemplating the informed consent regarding the use of the information and all the security and distance measures to avoid the spread of COVID-19.

The instrument used in the present study was a household survey, which was made up of a total of 6 sections that included: sociodemographic aspects of the household members, information related to the principal and secondary economic activities they carry out, elements about the physical characteristics of the home, the public policy programs that the home receives, the physical assets that the family has, and a section related to the generation of solid urban waste. All the information was captured and stored in spreadsheets and later imported into the STATA 17® statistical software for descriptive and econometric statistical analyzes.

Table 2. Sample size of study area

Municipality	Inhabitants	Sample size
Halacho	4,747	208
Izamal	9,640	206
Muna	3,029	205
Peto	5,599	102
Tekax	9,606	210
Tizimín	17,705	213
Total		1,144

Source: Own elaboration based on INAFED (2021)

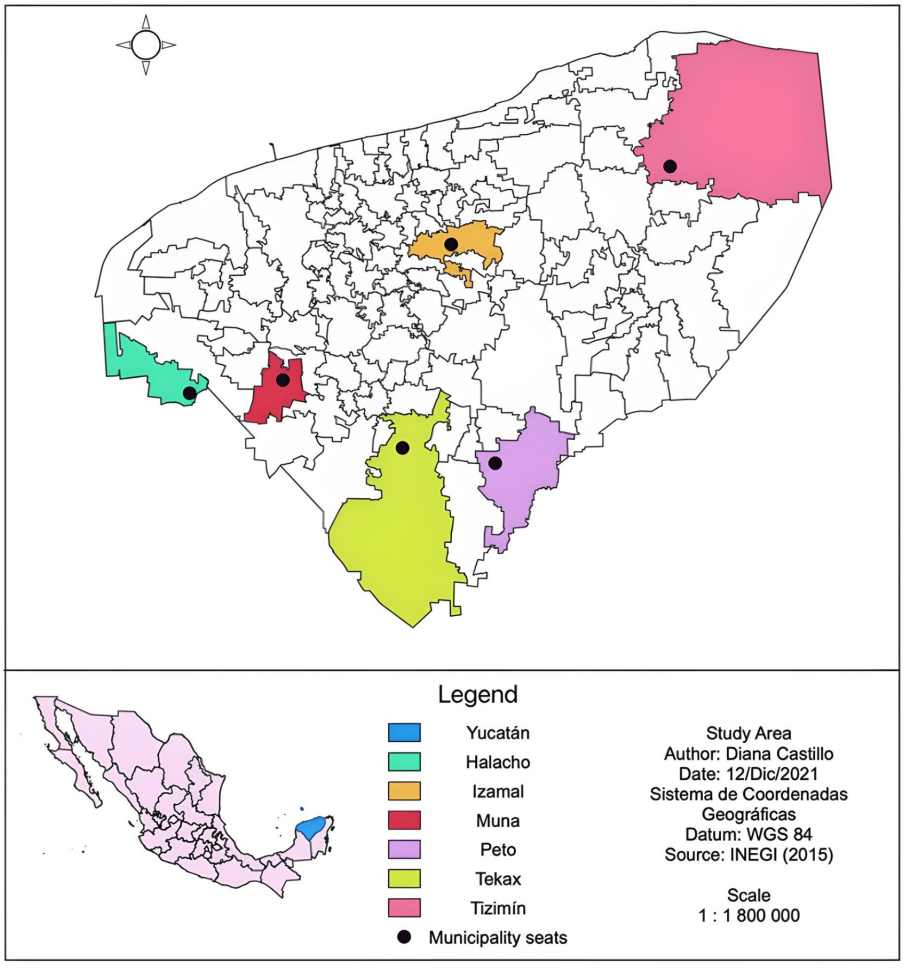

Figure 2. Study Area
Source: Own elaboration adapted from INEGI (2015).

2.1 Economic valuation method

The declared preferences method was used to estimate the total willingness to pay for the creation of an integral urban solid waste collection system. In particular, the contingent valuation method (CVM) was used, which offers a more direct approach to the interviewee (Tietenberg and Lewis, 2018). A CVM method provides information concerning WTP distribution for a proposed change in an environmental good (in this scenario, a reduction of pollution generated for the urban solid waste), and its goal is to measure an individual's monetary value for this item. The act of valuation implies a contrast between two situations, one with the item and one without it, therefore the answers reveal either an upper bound (in the case of a "no" answer) or a lower bound (in the case of a "yes" answer) (Tietenberg and Lewis, 2018; Carson and Hanemann, 2006).

The theoretical background of the method is composed by the structure of the utility function (Ferreira and Marques, 2015). The CVM relays on the survey response probability under the assumption that an individual maximizes her utility, the cumulative distribution function of WTP, G_c, and the corresponding probability density function, g_c, depends on the form of the survey questions (Hoyos and Mariel, 2010). We use an open-ended question format where individuals were asked to state their maximum WTP directly, A, the probability that the individual's WTP is equal to A, is:

$$Pr\left(WTP = A\right) \equiv g_c\left(A\right) \tag{1}$$

Obtaining the WTP distribution for an open-ended question format assumes a linear regression on some covariates (Zy) and a normally distributed random term (ε), so that WTP is also normally distributed (Hoyos and Mariel, 2010):

$$WTP = \mu_{WTP} + \varepsilon = Z_y + \varepsilon \tag{2}$$

2.2 Specifications of the Tobit censored regression model for WTP ($)

A monetary value of the willingness to pay (WTP) of the interviews was obtained. However, this dependent variable presents a particular characteristic as it is "left" censored in 0 for all the responses of the individuals who decided not to be WTP, in such a way, there is no charge for this situation. Additionally, it is also censored to the "right", since values greater than zero in the WTP have a limit of $ 200 MX[4], that is, none of the interviewees were WTP more than $ 200 MXN per month for the creation of ISWMS.

Therefore, the Tobit model (Tobin, 1958) is the most suitable alternative to the ordinary least squares regression model (OLS). The lack of ability to recognize the censorship in the distribution of the responses on the OLS model causes inconsistent and biased estimation parameters (Del Saz-Salazar et al., 2020; Maddala, 1983).

The Tobit regression model can be defined as follows:

$$y_i^* = x_i^{'}\beta + \varepsilon_i \tag{3}$$

Where y_i^* is the dependent latent variable, x_i, is the i-th row of n $\times$ (p+1) data matrix X with p explanatory variables, β is a (p+1) $\times$ 1 vector of coefficients and ε_i is the error term which is independently distributed with mean 0 and variance σ^2. There are different types of censoring such as left, right, double, centrally, and progressively (Toker et al., 2021).

The estimation of the Tobit model is now essentially on the level of ordinary linear regression (Greene, 2018), where the log likelihood for the censored regression model is:

$$\begin{aligned} \ln L = & \sum_{y_t>0} -\frac{1}{2}\left[\ln\left(2\pi\right) + \ln\sigma^2 + \frac{\left(y_i - x_i^{'}\beta\right)^2}{\sigma^2}\right] \\ & + \sum_{y_t=0} \ln\left[1 - \Phi\left(\frac{x_i^{'}\beta}{\sigma}\right)\right] \end{aligned} \tag{4}$$

Where the two parts correspond to the linear regression for the nonlimited observations and the relevant probabilities for the limit observation respectively (Greene, 2018).

[4]Exchange rate $ 20.73 mexican peso by $ 1 US dollar.

3 Results

The social, economic, and demographic characteristics of inhabitants and their households (HH) are reported in Table 3, were 41% of the household head is a man, the age average is around 50, and most of them (57%) speak local language: Maya. Most of the heads of household haven't finished high school (8.78 years of study). The annual income is around $ 2,720 US dollar per-capita.

Figure 3 identifies the urban solid waste generated with greater frequency in the interviewed households, the following stand out: bone and animal skin remain (93.53%), PET bottles (93%), food wrappers (92.48%), cleaning products (92.3%), food scraps (90.38%), light bulbs (89.07%), plastic in general (87.3%), cans (84.23%), toilet paper (83.3%) and, wood (82.25%). There is great value in recycling or the circular economy markets within the waste generated by households such as PET, cans, wood, and food wrappers. This factor is vital since the integral waste management system must consider reusing this type of waste.

Table 3. Sociodemographic characteristics of households

Variable	Mean	Standard deviation
Household head		
Sex (1=man)	0.41	0.49
Age	49.70	17.01
Speaks maya (1=yes)	0.57	0.49
Schooling years	8.78	4.01
Households' characteristics		
Family size	2.51	1.54
Number of rooms	2.00	1.06
Has a cellphone (1=yes)	0.89	0.31
Has a tricycle (1=yes)	0.36	0.48
Has a car (1=yes)	0.14	0.35
Anual total income ($MXN)	56,385.78	66,114.94

Source: Data collected, n= 1,144 households

Figure 4 presents the distribution of the USW generated in the households interviewed by their destination. As it is known waste collection handles some of the USW, however, the final disposal of other waste is burnt, sold, recycled, composted, used for animal food, given away, and dumped in landfills, streets, wells, and ground holes. According to the results obtained in the private dwellings, the following elements can be highlighted:

- Trash burning: The 24% of household burn toilet paper; the 24%, wood or gardening wastes; the 17%, food wrappers; the 16%, cardboard; and the 9%, domestic products.

- Waste collection: The 86% of households dispose light bulbs for trash collection; the 81%, domestic products, the 74%, toilet paper, the 73%, food wrappers; the 65%, tetrapak; the 58%, plastic in general; the 56%, glass; the 54%, medicines; the 59%, cans; the 47% of batteries; the 44%, home appliances; the 41%, cardboard; the 40% pet bottles; to a lesser degree, other.

- Sales: the households interviewed reported selling some of their waste to the USW. The 22% sale pet bottles; the 19%, metal; the 15%, cans; the 11%, aluminum; the 6%, plastic in general; and the 4% tetrapak.

- Compost: USW are useful to produce compost. The 3 USW mainly used for this purpose are wood or gardening wastes, in the 20% of households; manure, in the 11% and lastly food scraps, in the 7%.

- Animal food: USW can be used as animal food, especially in rural households that raise backyard animals. The main 3 used for this are bone and animal skin remaining the 60% of the households, food scraps, in the 49% and nixtamal in the 9%.

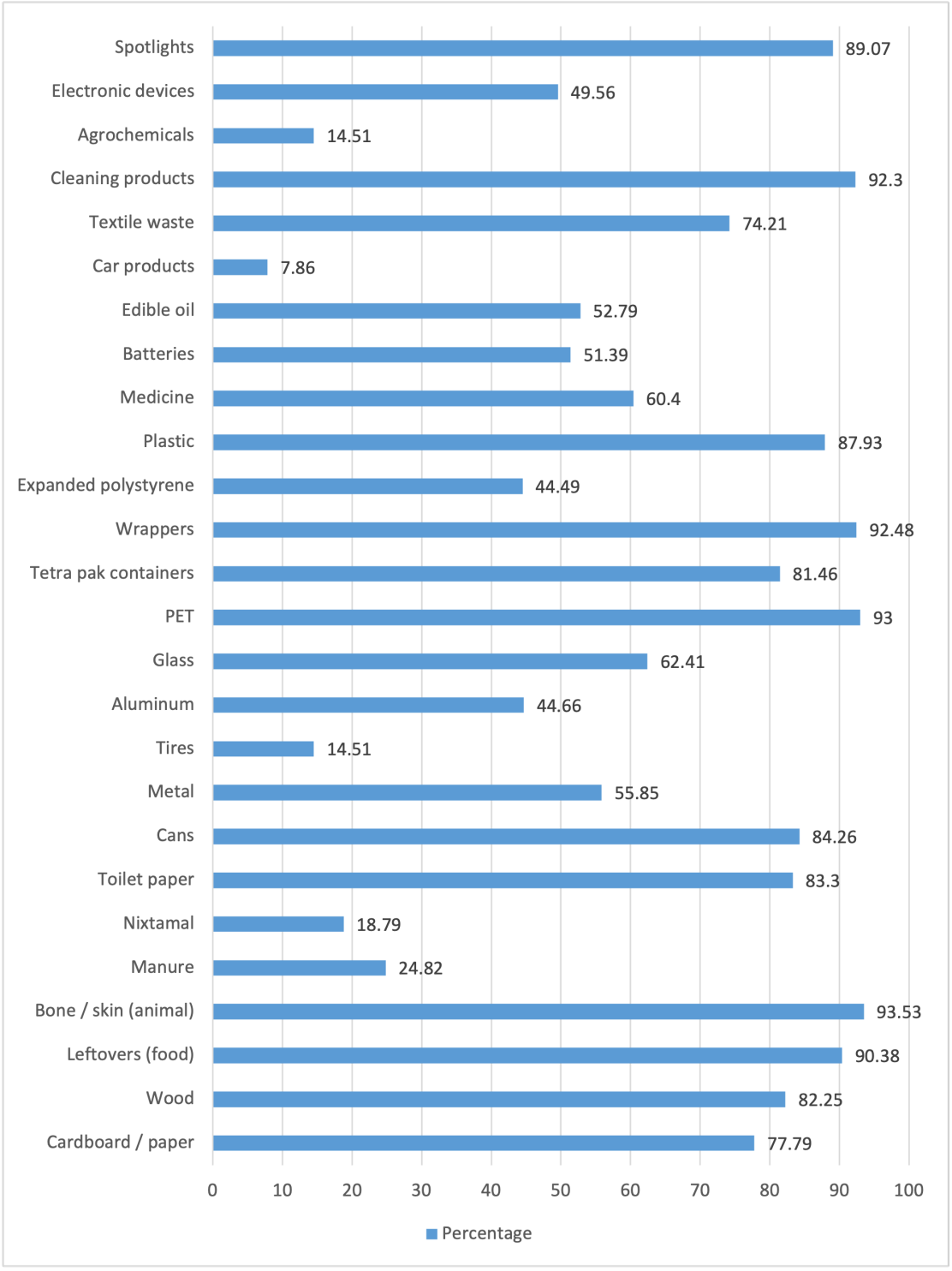

Figure 3. Percentage of households that generated Urban Solid Waste
Source: Own elaboration from data collected

In the description of the groups by their willingness to pay for creating an Integral Urban Solid Waste collection system in the municipalities, the results were as follows: 69.75% of the households interviewed declared they were willing to pay. The average payment amount is 17.65 Mexican pesos (0.85 US dollar).

The sociodemographic aspects that make the households different for their willingness to pay are described in Table 4. The results show that Mayan speaking (t = 3.33), years of education (t = 2.44), number of rooms in the house (t = 4.99), possession of a cell phone (t = 2.59), tricycle (t = 4.38) and a car (t = 3.89) make these groups different. In this sense, it is observed that households where the Mayan language predominates in general, are not willing to pay, as well as households that present fewer physical assets of the household.

The mean of WTP varies from one municipality to another. It is possible to observe in Figure 5 that in Muna, the WTP is barely above 10 pesos and is the lowest of all municipalities studied. While Halacho and Tekax are below 15 pesos, but up to 10. The WTP in Peto is above 15, but below 20 pesos. The WTP in Izamal is over 20 pesos, but the highest mean of WTP is in Tizimín, with 26.90 pesos.

The following Figure (6) shows the supervenience rate for more detailed information where the frequencies of occurrence of the remaining monetary value assigned can be observed by the interviewees.

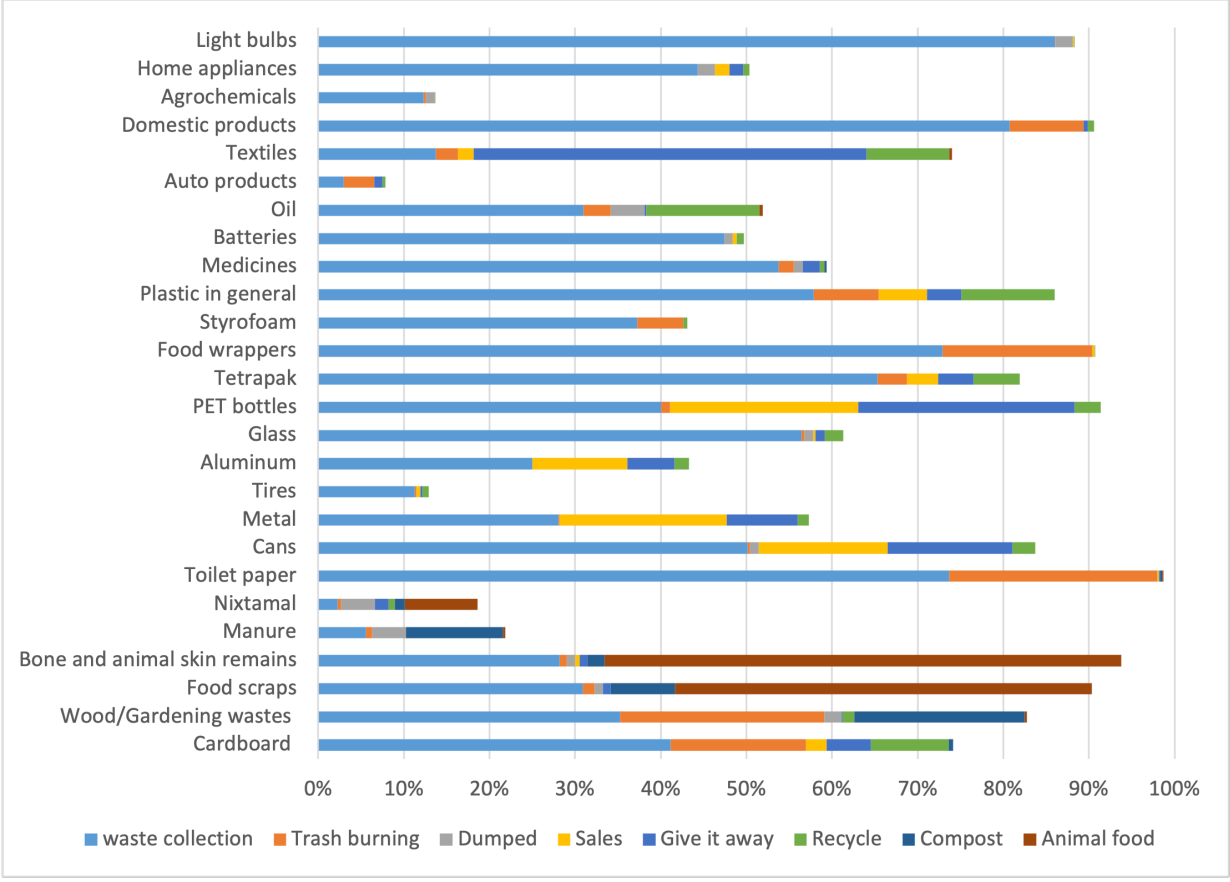

Figure 4. Destination of urban solid waste generated by households (%)
Source: Own elaboration from data collected

Households that declared not being willing to pay for an integrated solid waste collection system agreed on the following reasons:

- There is insufficient household income.
- There is no habit of paying for garbage collection.
- It is an additional expense for the home.
- There is already a free collection of waste.
- Distrust on the part of consumers because the current system does not function properly.

With the evidence of the descriptive information, the Tobit model was applied to identify the socioeconomic factors that influence the probability of a more significant monetary amount in people's willingness to pay. In total, six statistically significant variables were identified. Some of those variables are on the one hand; speaking Mayan by the head of the household and having a tricycle at home as an asset reduces the probabilities of making a higher payment. On the other hand, the years of education and variables associated with material improvements in the house, such as a more significant number of rooms, having a cell phone and a car, positively affect the probabilities of making a greater willingness to pay. The results are shown in Table 5.

Table 4. Sociodemographic aspects of the households interviewed regarding their WTP

Variable	Household is willing to pay (n=798)	Household is not willing to pay (n=346)	|t|
Household head			
Sex (1=man)	0.41	0.42	0.44
Age	49.34	50.52	1.08
Speaks maya (1=yes)	0.54	0.65	**3.33**
Education	8.97	8.34	**2.44**
Hosehold aspects			
Family size	2.48	2.57	0.91
Number of rooms	2.10	1.76	**4.99**
Has a cellphone (1=yes)	0.90	0.85	**2.59**
Has a tricycle (1=yes)	0.32	0.45	**4.38**
Has a car (1=yes)	0.17	0.08	**3.89**
Anual total income per cápita ($MXN)	3,025.23	2,729.95	1.33

Source: data collected.

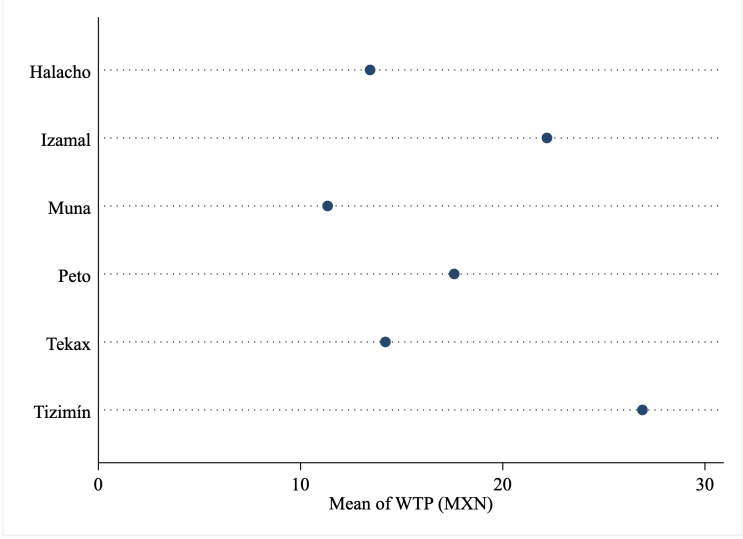

Figure 5. Mean of WTP from municipalities studied
Source: Own elaboration from data collected

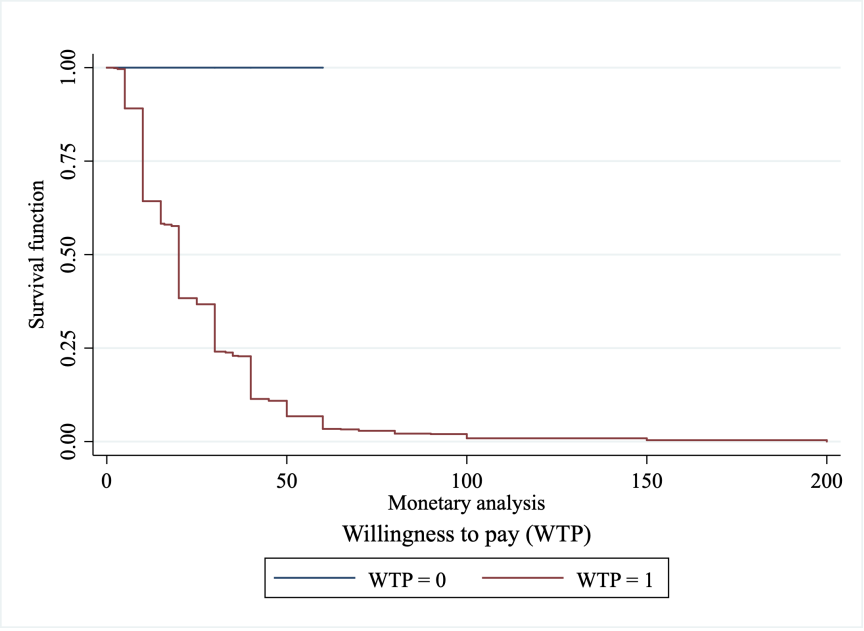

Figure 6. Survival estimates of WTP
Source: Own elaboration from data collected

4 Discussions

The results of academic research are useful by regional authorities to establish IUSWM plans and programs capable of meeting regional waste management demands (Gidarakos et al., 2006). However, there is a lack of studies on how rural populations manage their solid waste (Taboada-González et al., 2013). Findings from existing studies indicate that local government waste collection is deficient since a significant part of this population lacks the service (Del Carmen-Niño et al., 2019). There are also informal trash collection systems in rural areas, for which the residents must pay a fee (Aljaradin et al., 2015).

In addition, the results of the present study reveal that rural dwellers use organic waste to feed their animals or in the production of compost, (Del Carmen-Niño et al., 2019; Juárez López, 2009); this tendency shows potential for the application of the component of re-utilization of USW. Furthermore, some households use trash burning as a cultural practice or because there is no trash collection available (Del Carmen-Niño et al., 2019; Friesen-Pankratz et al., 2011), which is one of the practices that IUSWM try to avoid since waste burning is a path for air pollution. A high percentage of food wrappers are notable (92.48%), as it has been observed by other studies in different countries, this practice is related to the change in consumption patterns (Gidarakos et al., 2006).

Previous studies reveal that the WTP for an urban solid waste recollection system is related to the value that inhabitants assign to the quality of the environment in their community, and other socioeconomic elements as income, gender, age, level education, family size, offspring, environmental ethics, and confidence in government (Ibarrarán et al., 2003; Quispe Mamani et al., 2020). In this case, the associated factors include not speaking Mayan, higher number of assets and more rooms in the house.

Nonetheless, there is a 69.75% of the households interviewed willing to pay, which represents an opportunity for the government to establish appropriate plans and programs of Urban Solid Waste Management in partnership with a private entity. This percentage is lower than the one presented by Song et al. (2016), which obtained 85.5% positive responses towards WTP in a study conducted in Macau, China.

It was possible to establish the mean willingness to pay in the study area, which was 17.65 Mexican pesos (0.85 US dollar) per household, significantly lower results than those obtained by Ferreira and Marques (2015) in Portugal (2.59 euros) or that reported by Koford et al. (2012) in the United States ($2.29 USD), as well as the 10.16 soles estimated by Colquehuanca Vilca et al. (2020) in Peru, the $4.79 USD obtained by Song et al. (2016) in China and Kayamo (2022) in Ethiopia with $0.62 USD per person. The variation might be linked to the different income between countries, an element that exceeds the scope of this study.

Table 5. Results of the Tobit regression model

Variable	Coefficient	Std. Error	z	P>|z|
Household head				
Sex (1=man)	1.99	1.76	1.13	0.259
Age	0.05	0.06	0.96	0.337
Speaks maya (1=yes)	-3.74	2.00	**-1.87**	0.022
Schooling years	0.43	0.25	**1.68**	0.093
Household aspects				
Family size	0.92	0.57	1.61	0.106
Number of rooms	4.05	0.81	**5.00**	0.000
Has a cellphone (1=yes)	10.95	2.95	**3.70**	0.000
Has a trycicle (1=yes)	-7.52	1.86	**-4.04**	0.000
Has a car (1=yes)	8.00	2.46	**3.25**	0.001
Constant	-12.19	5.81	2.10	0.036

n=1,144; uncensored=800, left-censored=341, right-censored=3; Chi^2=100.09 prob>Chi^2=0.000
Source: Own elaboration from data collected

5 Conclusions

The contingent value method applied to implementing a solid waste collection system in semi-urban communities in Yucatán was successfully applied in this study. Its effectiveness as a method of direct assessment of the change of a situation involving municipal solid waste is tested in the rural and peri-urban cities in Yucatan, Mexico.

The methodology used allows the establishment of market-based solutions that reconcile the ability to pay of the actors involved; however, since they are directly associated with public service (solid waste collection), it is necessary to develop complementary public policies that address the proper disposal of waste, as well as its reduction. The results of this study contribute to better understanding the relationship between the inhabitants of growing cities and to be able to address these problems that have economic, social, and environmental consequences.

The socioeconomic factors that affect the willingness to pay and that were statistically significant allow us to approach the household profile that generates solid urban waste. This information can help future studies that allow establishing an optimal price for the municipal solid waste collection system, also considering the following elements described below to guarantee the financing and economic sustainability of the system. Although there are cultural and social elements rooted in solid waste collection, this integrated system may be accompanied by other types of economic incentives to modify consumers' behavior towards something more beneficial for the environment, such as the homes' income. An example of the that could be the payment of the proper disposal of waste with high recycling value.

In other countries, a proper public-private urban solid waste management partnership can result an effective strategy to solve the USW management problems Aliu et al. (2014); Bhuiyan (2010); Rode (2011).

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Conflicts of interest

The authors declare that they have no conflict of interest.

Author Contributions

Conceptualization, FIHC; formal analysis, FIHC; research, FIHC and DECL; methodology, FIHC; monitoring, validation and visualization, FIHC, DECL, JBG and MPMG; writing-original draft, FIHC, DECL, JBG and MPMG; acquisition financing, MPMG; writing-review and editing, FIHC, DECL and MPMG.

References

Aliu, I., Adeyemi, O., and Adebayo, A. (2014). Municipal household solid waste collection strategies in an african megacity: Analysis of public private partnership performance in lagos. *Waste Management Research*, 32:67–78. Online:https://n9.cl/evm2r.

Aljaradin, M., Persson, K., and Sood, E. (2015). The role of informal sector in waste management, a case study; tafila-jordan. *Resources and Environment*, 5(1):9–14. Online:https://n9.cl/v7zfm.

Bhuiyan, S. (2010). A crisis in governance: Urban solid waste management in bangladesh. *Habitat International*, 34(1):125–133. Online:https://bit.ly/3si9G01.

Canul Bacab, F. and May Hoil, P. (2016). El problema de la basura en el interior del estado de yucatán.(versión imprimible). online:https://n9.cl/1y3g7y. *Reaxión*, 3(2).

Carson, R. and Hanemann, M. (2006). *Handbook of Environmental Economics*, chapter Contingent Valuation, pages 821–936. Elsevier.

Colquehuanca Vilca, J., Colquehuanca Calli, Á., Gallegos Ramos, N., and Calatayud Mendoza, A. (2020). Disposición a pagar por eliminación de residuos urbanos (municipalidad provincial de tambopata, madre de dios, perú). *Revista de Investigaciones Altoandinas*, 22(4):329–337. Online:https://n9.cl/g485h.

Couto Benítez, I., Hernández, A., and Sarabia, C. (2012). La gestión integral de los residuos sólidos urbanos en juárez: lecciones innovadoras para otros municipios. *Revista Pueblos y Fronteras Digital*, 7(13):178–209. Online:https://bit.ly/3MCcBHZ.

da Silva, L., Prietto, P., and Korf, E. (2019). Sustainability indicators for urban solid waste management in large and medium-sized worldwide cities. *Journal of Cleaner Production*, 237:117802. Online:https://n9.cl/3iooz.

Del Carmen-Niño, V., Rodríguez Herrera, A., Juárez-López, A., Sampedro-Rosas, M., Reyes-Umaña, M., and Silva-Gómez, S. (2019). La importancia de la participación y corresponsabilidad en el manejo de los residuos sólidos urbanos. online:https://n9.cl/leysl. *Acta universitaria*, 29.

Del Saz-Salazar, S., Feo-Valero, M., and Vázquez-Paja, B. (2020). Valuing public acceptance of alternative-fuel buses using a latent class tobit model: A case study in valencia. *Journal of Cleaner Production*, 261:121199. Online:https://n9.cl/vja2l6.

Diario Oficial de la Federación (2003). Ley general para la prevención y gestión integral de los residuos. Online:https://n9.cl/z91u0.

El-Messery, M., Ismail, G., and Arafa, A. (2009). Evaluation of municipal solid waste management in egyptian rural areas. *J Egypt Public Health Assoc*, 84(1-2):51–71. Online:https://n9.cl/qb38z.

Ferreira, S. a. and Marques, R. (2015). Contingent valuation method applied to waste management.

Resources, Conservation and Recycling, 99:111–117. Online:https://n9.cl/2k1nw.

Friesen-Pankratz, B., Bautista, L., de Jesús Meza, Z., Reyes, S., and Wiebe, A. (2011). El manejo de los residuos en una comunidad rural de méxico: Prácticas actuales y planes futuros. *Hacia la sustentabilidad: los residuos sólidos como fuente de energía y materia prima*, pages 451–455. Online:https://n9.cl/z0z16.

Gidarakos, E., Havas, G., and Ntzamilis, P. (2006). Municipal solid waste composition determination supporting the integrated solid waste management system in the island of crete. *Waste management*, 26(6):668–679. Online:https://n9.cl/xhtytf.

Greene, W. (2018). *Econometric Analysis*. Pearson.

Hoyos, D. and Mariel, P. (2010). Contingent valuation: Past, present and future. *Prague economic papers*, 4(2010):329–343. Online:https://n9.cl/8bva6.

Huamaní Montesinos, C. (2017). Análisis socioeconómico y ambiental del reaprovechamiento y disposición final de los residuos sólidos en la ciudad de juliaca, san román, puno-2017. Master's thesis, Universidad Nacional Del Altiplano.

Hui, Y., Li'ao, W., Fenwei, S., and Gang, H. (2006). Urban solid waste management in chongqing: Challenges and opportunities. *Waste management*, 26(9):1052–1062. Online:https://n9.cl/zwnl2.

Ibarrarán, M., Islas, I., and Mayett, E. (2003). Valoración económica del impacto ambiental del manejo de residuos sólidos municipales: estudio de caso. *Gaceta ecológica*, (67):69–82. Online:https://n9.cl/cwipp.

INAFED (2021). Sistema nacional de información municipal. secretaría de gobernación. techreport, Secretaría de Gobernación.

INEGI (2015). Biblioteca digital de mapas. Página web. Online:https://bit.ly/476WbQ1.

Juárez López, A. (2009). *Manejo de residuos sólidos urbanos para los cauces fluviales de la zona urbana y suburbana de Acapulco, Guerrero. Chilpancingo*. PhD thesis, Universidad Autónoma de Guerrero.

Kayamo, S. (2022). Willingness to pay for solid waste management improvement in hawassa city, ethiopia. *Journal of Environmental Management*, 302:113973. Online:https://n9.cl/8p6m2.

Kaza, S., Yao, L., Bhada-Tata, P., and Van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050*. World Bank Publications.

Koford, B., Blomquist, G., Hardesty, D., Troske, K., Hughes-Morgan, M., and Morgan, F. (2012). Estimating consumer willingness to supply and willingness to pay for curbside recycling. *Land Economics*, 88(4):745–763. Online:https://n9.cl/zjcid.

Maddala, G. (1983). *Limited-dependent and qualitative variables in econometrics*. Cambridge university press.

Marín García, A. and Quintanilla Jerezano, J. (2007). *Diagnóstico del manejo de residuos sólidos urbanos en el Municipio de Acatlán, Veracruz. Xalapa.* PhD thesis, Universidad Veracruzana.

Quispe Mamani, J., Guevara Mamani, M., Marca Maquera, V., Mamani Sonco, V., and Marca Maquera, H. (2020). Estimación de la disposición a pagar por un sistema de recolección mejorado de residuos sólidos domésticos en la ciudad de juliaca-2020. *Ciencia y Desarrollo*, (26):77–87. Online:https://n9.cl/crfunm.

Rode, S. (2011). Public private partnership in solid waste management in municipal corporations of mumbai metropolitan region. *Management Research and Practice*, 3:23–38. Online:https://n9.cl/nhf9z.

Seadon, J. (2006). Integrated waste management-looking beyond the solid waste horizon. *Waste management*, 26(12):1327–1336. Online:https://n9.cl/vblpi.

Secretaría de Desarrollo Sustentable (2021). Yucatán, primer estado del país en realizar un programa de manejo de residuos específico para cada uno de sus 106 municipios. Página web del Gobierono del Estado de Yucatán, online:https://bit.ly/3FStp9F.

Secretaría de Desarrollo Social (2013). Generación de residuos sólidos urbanos. techreport, Dirección General de Equipamiento e Infraestructura en Zonas Urbano-marginadas.

Secretaría de Medio Ambiente y Recursos Naturales (2017). Residuos sólidos urbanos y de manejo especial. Secretaría de Medio Ambiente y Recursos Naturales. Online:https://n9.cl/c36n.

Song, Q., Wang, Z., and Li, J. (2016). Residents' attitudes and willingness to pay for solid waste management in macau. *Procedia environmental sciences*, 31:635–643. Online:https://n9.cl/r3fz3.

Srivastava, V., Ismail, S., Singh, P., and Singh, R. (2015). Urban solid waste management in the developing world with emphasis on india: challenges and opportunities. *Reviews in Environmental Science and Bio/Technology*, 14:317–337. Online:https://n9.cl/kufp0.

Taboada-González, P., Aguilar-Virgen, Q., Cruz-Sotelo, S., and Ramírez-Barreto, M. (2013). Manejo y potencial de recuperación de residuos sólidos en una comunidad rural de méxico. *Revista Internacional de contaminación ambiental*, 29:43–48. Online:https://n9.cl/adg08.

Tchobanoglous, G. and Kreith, F. (2002). *Handbook of solid waste management*. McGraw-Hill.

Tietenberg, T. and Lewis, L. (2018). *Environmental and Natural Resource Economics*, chapter Environmental and Natural Resource Economics, page 73–83. Routledge, New York.

Tobin, J. (1958). Estimation of relationships for limited dependent variables. *Econometrica: journal of the Econometric Society*, 26:24–36. Online:https://n9.cl/q6kay.

Toker, S., Özbay, N., Şiray, G. U., and Yenilmez, I. (2021). Tobit liu estimation of censored regression model: an application to mroz data and a monte carlo simulation study. *Journal of Statistical Computation and Simulation*, 91(6):1061–1091. Online:https://bit.ly/49yEj1W.

Vij, D. (2012). Urbanization and solid waste management in india: present practices and future challenges. *Procedia-Social and Behavioral Sciences*, 37:437–447. Online:https://n9.cl/p48af.

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Characterization of the environmental attitudes and practices of the urban population of Puno, Andean Plateau

Actitudes y prácticas ambientales de la población urbana de Puno, Altiplano Andino

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Abstract

During the last decades in Puno, Peru, the problem of contamination has worsened due to the combined action of the disorderly growth of the urban population, poor management of solid waste, discharge of untreated sewage into the bay of Lake Titicaca and practices of inadequate sanitation and hygiene, severely affecting the environment and human health. The objective of the study was to characterize the pro-environmental attitudes and behaviors of the city's population of Puno in relation to sanitation, pollution and environmental management. The research is non-experimental, quantitative, cross-sectional, descriptive, correlational and micro level of analysis. The universe of study was the population over 18 years of age in the urban area, which comprises 97,264 inhabitants; the sample, determined at simple random, was 382 people. A structured questionnaire was applied. Descriptive and inferential analysis and hypothesis testing were performed with SPSS statistical software. The results indicate that the environmental attitudes of the majority of the population are positive regarding factors and sources of pollution and effects on human health. On the contrary, environmental practices are inadequate in environmental management in the home and health and hygiene conditions in the home. It is concluded that the sustainable improvement of pro-environmental attitudes and behaviors demands a new public policy of environmental education, whose implementation incorporates the effective participation of civil society based on an incentive system.

Keywords: Environment, behavior, concern, contamination, sanitation.

Resumen

Durante las últimas décadas en Puno, Perú, la problemática de la contaminación se fue agudizando por la acción combinada del crecimiento desordenado de la población urbana, gestión deficiente de residuos sólidos, descarga de aguas servidas sin tratamiento en la bahía del lago Titicaca y prácticas de sanidad e higiene inadecuadas; situaciones que afectan severamente el ambiente y la salud humana. El objetivo del estudio fue caracterizar las actitudes y comportamientos proambientales de la población de la ciudad de Puno en relación al saneamiento, la contaminación y la gestión ambiental. La investigación es no experimental, cuantitativa, trans¬versal, descriptiva, correlacional y nivel de análisis micro. El universo de estudio fue la población mayor de 18 años del área urbana, que comprende 97.264 habitantes; la muestra, deter¬minada al azar simple, fue de 382 personas. Se aplicó un cuestionario estructurado. El análisis descriptivo, inferencial y prueba de hipótesis se realizó con el software estadístico SPSS. Los resultados señalan que las actitudes ambientales de la mayoría de la población son positivas respecto a factores y fuentes de contaminación y efectos en la salud humana; contrariamente, las prácticas ambientales son inadecuadas en gestión ambiental en el hogar y condiciones de sanidad e higiene en la vivienda. Se concluye, que la mejora sostenible de actitudes y comportamientos proambientales, demanda de una nueva política pública de educación ambiental, cuya implementación incorpore la participación efectiva de la sociedad civil con base a un sistema de incentivos.

Palabras clave: Ambiente, comportamiento, contaminación, preocupación, saneamiento.

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1 Introduction

Concern for environmental problems began to be more openly discussed in the 1970s (Vargas et al., 2019). In the 1980s, humans manifested that concern for the environment (Álvarez and Vega, 2009) and in the early 1990s, it was referred to in the global context at the Rio de Janeiro Earth Summit (Agenda 21, 1992).

From the perspective of the Social Sciences, research on this concern has been expressed in theoretical formulations, methodological proposals and empirical treatments that allow the understanding of human beings to interpret the problem (Amérigo et al., 2012), expressed in environmental concerns and their correlation in pro-environmental behaviors.

There is a vast and important scientific production on the subject made from different perspectives. In fact, on the one hand, there are studies with one-dimensional pro/anti-environmentalism approaches in the relationship between self and nature, with emphasis on safety, health and environment (Vargas et al., 2019) or environmental education by gender (Pérez-Franco et al., 2018). On the other hand, studies with two-dimensional structures with strong emphasis on cognitive processes, such as anthropocentrism-ecocentrism (Thompson and Barton, 1994), new ecological paradigm (Dunlap et al., 2000) and use-preservation (Milfont and Duckitt, 2010) or approaches with a strong emphasis on affective and emotional processes, such as: emotional affinity (Kals et al., 1999), identity (Clayton, 2003) and articulation with nature (Vining et al., 2008) whose methodological frameworks were taken for empirical studies (Suárez et al., 2007). As well as studies with tripartite factorial structures: selfishness, socio-altruism and biospherism (Amérigo et al., 2005); Anthropocentrism, Progress and Naturalism (Hernández et al., 2001) but also studies under theoretically integrated four-dimension structures: apathy, anthropocentrism, connectivity and emotional affinity (Amérigo et al., 2012).

However, studies on environmental behavior are scarce or little diffused, moreover, there are almost nonexistent related to the relationship between attitudes with measures of environmental behavior, being pioneers, in this line, the conceptual proposals about education in the subject made by Álvarez and Vega (2009) and exploratory studies of Amérigo et al. (2012); Amérigo and García (2014); Amérigo et al. (2017); Favara and Moreno (2020); Rivera-Jacinto and Rodríguez-Ulloa (2009); Hernández et al. (2001); Palavecinos et al. (2016). Most of these empirical studies have taken as units of analysis mainly university students from Spain, Mexico, Brazil, Chile, Argentina, Peru, and complementarily older people in Costa Rica and Spain.

In developing countries such as Peru, most diseases affecting people living in extreme and vulnerable poverty are largely attributable to basic needs related to environmental sanitation (World Health Organization, 2019), solid waste management given the huge volume that occurs in urban areas and with the difficulties to eliminate them, exacerbated by inadequate environmental practices, which ultimately denote a picture that arouses concern in different sectors of society that try to alert and sensitize the population and authorities. The solutions and responses to the problem are very diverse at the global, regional and national levels, depending on economic, geographical, political, educational and cultural characteristics (Velásquez Patiño, 2008).

In Puno, the situation becomes even more critical, since the wastewater is discharged into the bay of Titicaca Lake without proper treatment, coupled with the poor management of urban solid waste, the collapse of the system of oxidation ponds, the dismantling caused by the urban construction system, the fragility and separation of technological, institutional and social factors, which severely affect the environment and human health (Tumi Quispe, 2014).

Faced with this complex and multideterminative problem, the study aims to respond to the following concern: what are the expressions and relationship of pro-environmental attitudes and practices of the population of the city of Puno on sanitation, pollution and environmental management? The purpose of the research is to contribute to the design of a public policy of environmental education that serves as a guiding framework for citizen behavior and institutional management related to the environment.

2 Materials and Methods

2.1 Area of study

The study context is the city of Puno, which is comprised from the west bank of Titicaca Lake, in the inner bay formerly called Paucarcolla, on a slightly undulating surface, surrounded by hills. Titicaca Lake, located in the high plateau area between Peru and Bolivia, at an altitude of 3 810 m above sea level, with a total area of 8.167 km^2, a maximum amplitude of 125 km and an extension of 400 km, is considered the highest navigable lake in the world, its importance is supported by the richness of its biodiversity, aquatic fauna and tourist potential (Aranibar Ramos and Patiño Huayhua, 2022; Tumi Quispe, 2016); but paradoxically, its inner bay has been subject to an increasing pollution process (Luca and Ticona, 2006) and severe eutrophication (Jimenez et al., 2016; Fontúrbel-Rada, 2003) product of anthropic action (Valderrama and Canales, 2007), with negative effects on human health (Miranda Aliaga, 2004; Valderrama and Canales, 2007) and the atmosphere.

2.2 Research design

The research design is non-experimental (since the study does not establish the manipulation of independent variables, but assumes unrestricted respect for the natural and social environment) and transversal (the process of collecting information and measuring variables was performed by establishing a single temporal cut). The focus of the research is quantitative; it is socio-environmental because its dimension of analysis; the level of analysis is micro because it is descriptive and correlational.

2.3 Population, sampling type and sample

The universe consisted of the population over 18 years old living in the urban area of Puno, comprising 97 264 inhabitants (Instituto Nacional de Estadística e Informática, 2018); the operational population is 382 people, randomly determined without replacement and considering the 95% confidence degree and a margin of error of 0.05.

2.4 Data collection technique and instrument

The data collection technique was the survey, through a structured questionnaire applied to heads of families between October and December 2018. Environmental attitudes were measured with 12 items grouped into three dimensions: factors of contamination in the house (water quality, garbage collection, unpaved streets, domestic animals in the house and sewer obstruction), sources of pollution of the Titicaca Lake Bay (wastewater, solid waste, collapse of the oxidation lagoon), effects of factors and sources of pollution on human health (neuropsychological, digestive, dermatological, and ocular symptoms). The measurement of environmental behaviors was carried out through 14 items grouped into three types of behaviors: environmental practices in the home (type of container for storing solid waste (SW), place of storage of SW in the house, frequency of disposal and final disposal), conditions of access to water services in the house (sources of water supply in the house, access and home distribution of water, installed and operational hygienic services) and sanitary and hygiene practices in the home (frequency of hand washing after handling SW, place of disposal of feces, cleaning frequency of the bathroom). The assessment of the dimensions of environmental attitudes and practices was performed under the vigesimal system (0 to 20 points), considering in each item different categories in accordance with the current regulations on environmental sanitation.

In addition, the study used secondary sources, referring to information on the population and housing census (Instituto Nacional de Estadística e Informática, 2018), as well as diagnoses and evaluation studies on pollution and eutrophication of the Titicaca Lake basin carried out by the regional environmental institutions.

2.5 Processing and statistical analysis

Data processing was performed with SPSS statistical software, as well as descriptive, inferential and hypothesis testing analysis. The statistical test performed was non-parametric through the probability distribution of the chi-square to establish the correlation degree between environmental attitudes (dimensional optics) and environmental behavior

(three-dimensional optics) that possesses the population of Puno, denoting that more than half of the population possesses positive attitudes (62%), on the contrary, environmental practices are inadequate in most of the population (55.2%).

Chi square (Ritchey, 2002; Flores et al., 2017) was used because it responds to the fact that the central variables of the study, given their nominal or ordinal nature, did not make possible to perform statistical tests with a higher level of precision and depth.

3 Results

The urban population of Puno presents the following basic features. Regarding the main occupation, half of the population (50,79%) is made up of independent workers and one out of four is employed; in four out of five heads of families their income is less than 2000 thousand soles; while in 1 out of 10 their income is less than the minimum living income (US $ 232), which means that these families are within the belt of poverty or extreme poverty. In relation to the level of education of the heads of households, most completed higher education (64.92%) and to a lesser extent secondary education (29.84%). The majority (69.90%) own the houses, and a smaller proportion rent it (28.80%), which could imply a greater neighborhood identity and sense of belonging to the area they inhabit, which could condition their attitudes and environmental practices regarding the pollution of Titicaca Lake.

In this context, the assessment of environmental attitudes and practices of the population of Puno focuses on the reality, conditioned both by the economic, social and cultural context, as well as by the level and degree of effectiveness of the regional environmental institutionality to promote an environmental education program that contributes to the construction of an environmental and ecological awareness of social actors in a sustainable perspective (Figure 1).

At the structural level, the proposed conceptual model establishes as fundamental components environmental conceptual knowledge (ECK) and environmental ecological awareness (EEA). At the functional level, the model considers a process of articulation (relationship, entanglement, coexistence and dependence), which can be of concordance and/or discordance, of environmental conceptual knowledge that will have its correlation and expression in environmental attitudes (EA) and environmental and ecological awareness that is expressed in the environmental practices (EP) of social and institutional actors.

In this context, the characterization of attitudes (positive or negative) and environmental practices (adequate or inadequate) of the urban population of Puno, is carried out considering the following axes and dimensions of analysis. In the assessment of environmental attitudes, the expressions about pollution factors in the house, sources of pollution of Titicaca Lake and effects of pollution of Titicaca Lake on human health are considered. The assessment of environmental practices is related to environmental management in the home, access to water services in the home, and the health and hygiene conditions of the family in the home. The assessment of the relationships of pro-environmental attitudes and practices is established through the nonparametric chi-square statistical test.

3.1 Environmental Attitudes of the Urban Population of Puno

In general terms, the environmental attitudes of the population indicates that most of the heads of households have positive attitudes according to dimensions (factors of pollution in the house, sources of pollution of the Titicaca Lake and effects on human health) and categories of analysis (Figure 2):

- The positive attitudes of the population towards the factors of pollution in the house, indicates the prioritization of water quality (93.2%) and garbage collection (88.5%), being lower in the other categories of analysis.
- Attitudes towards sources of pollution in the bay are differentiated, emphasizing the negative effect of the collapse of oxidation ponds (84.3%) and wastewater (77.5%), which allows questioning the management of the municipal government; while the effect of poor solid waste management is smaller (56.8%), expressing the co-responsibility that families and the municipal government have in the final disposal of solid waste.

- Attitudes regarding the effects of pollution on human health emphasize the negative effect on the incidence of neuro-psychic (69.9%) and digestive (66.4%) symptoms, with less or no incidence in dermatological and ocular symptoms.

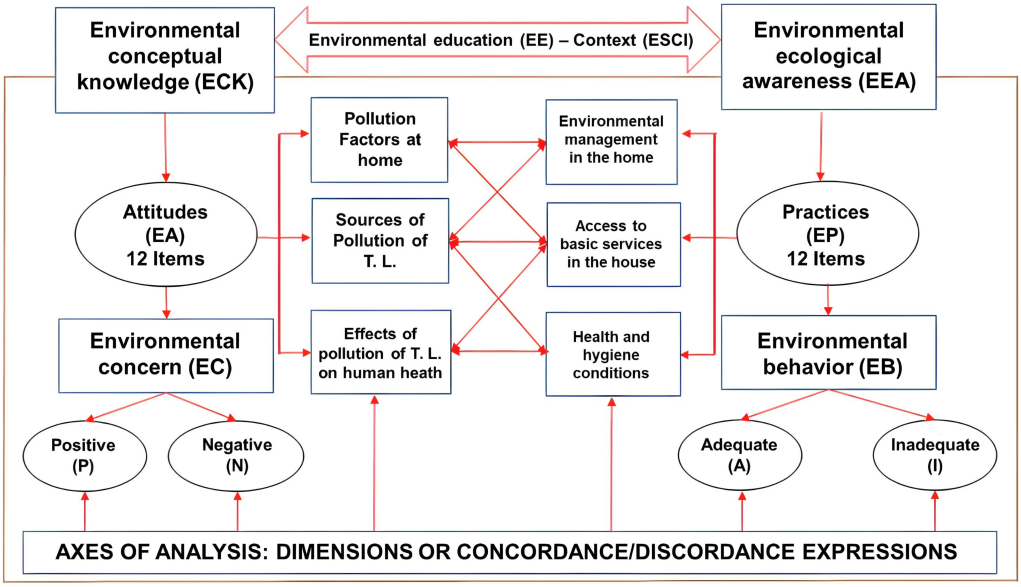

Figure 1. Model of relationships between attitudes and pro-environmental practices
Source: Own elaboration (2020)

On the other hand, the environmental attitudes of the population of Puno, considering the variables degree of education and gender of the heads of families, present several trends (Table 1):

- Pollution factors in housing, considering the level of education, denotes positive attitudes of the primary level that prioritizes the quality of water (100%) and garbage collection (95%), being lower in the population of the secondary and higher level. Gender shows a similar trend in the prioritization of pollution factors, but with a higher positive attitude in women (94.7%) compared to men (91%).
- Regarding sources of pollution of Titicaca Lake, the highest proportion of positive attitudes is present in the population of primary level that emphasize the negative effect of the collapse of the oxidation pond (100%) and to a lesser extent wastewater (85%); on these same factors, in the gender situation, men (86.5% and 82.4%) to a greater extent emphasize the negative effect.
- On the negative effects on human health of the factors and sources of pollution of the bay, the perception of the population is emphasized in the neuro-psychic and digestive symptoms, where the positive attitude is higher in the level of higher education (4 of 5 people) and of the males regarding the females.

Consequently, the study shows that the attitudes of most of the population (62%) are positive, but differentiated, given that in factors of contamination in the house predominates the quality of the water (93.2%) and garbage collection (88.5%); in sources of contamination of the bay of Titicaca Lake stand out the negative effect of the collapse of the oxidation ponds (84.3%) and wastewater (77.5%) and the effects on human health especially in the neuro-psychic (69.9%) and digestive symptoms (66.4%). Therefore, improvement of the population's pro-environmental concern is conditioned by the preventive action of the local and regional government not only to reduce the factors and sources of pollution with clean technologies, but also to implement mechanisms of participation, strengthening the sense of co-responsibility in civil society organizations.

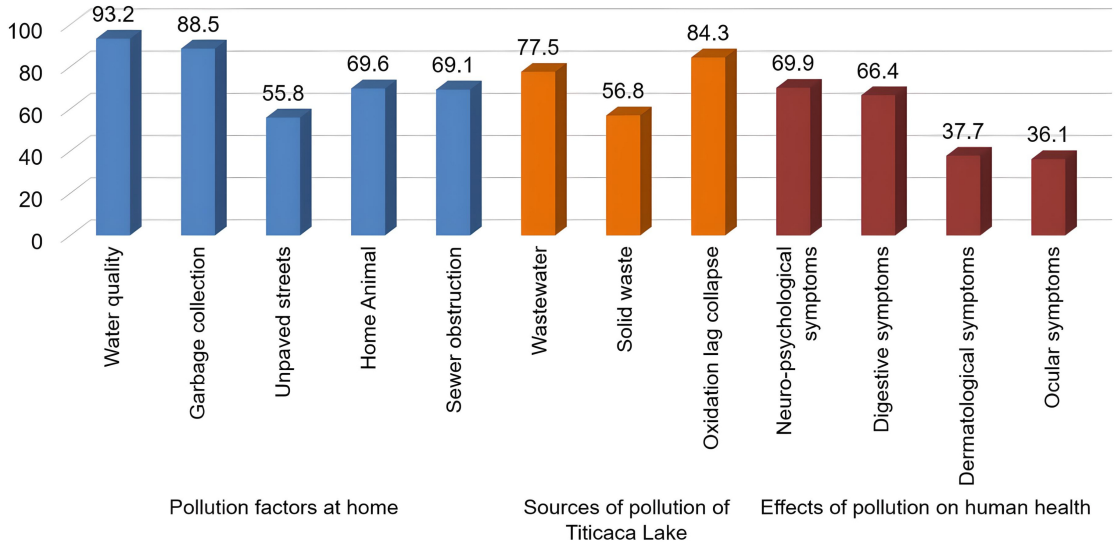

Figure 2. Positive environmental attitude of the urban population of Puno by dimensions and categories of analysis

3.2 Environmental practices of the urban population of Puno

The characterization of the environmental behavior of the population is carried out considering the dimensions of environmental management of the family in the house, the access to water in the house and conditions of health and hygiene.

3.2.1 Family environmental management at home

In general, the environmental practices of the family at home are related to the type of container for storing solid waste (SW), place in the house where SW are deposited, frequency of disposal of SW, final disposition of SW and frequency of hand washing after handling SW, all presenting different features (Figure 3):

- The containers for storing SW used by most families in the house indicates the predominance of the use of polyethylene bags (66.5%) and to a lesser extent waterproof containers with lid (26.4%).
- The temporary storage of urban solid waste denotes that the tendency to store in the courtyard of the house is dominant (77.23%), having the kitchen less significance (5.49%).
- Most families take out the solid waste from their houses on an interdaily basis (58.9%) and to a lesser extent daily (12.83%), showing a problematic situation, i.e., 1/3 of the population take out their waste weekly.
- As for the final disposal of solid waste as an intermediate process or temporary storage, it indicates that most families (88.74%) do it in the container directly or the collective deposit outside the house, considered these appropriate practices. A similar trend is observed in the practice of hand washing frequency.

On the other hand, the environmental practice of the population on solid waste disposal according to the level of education and gender presents the following characteristics (Table 2):

- Regarding the use of containers for solid waste storage according to the level of education, it shows that polyethylene bags are mainly used, especially those with primary level (100%), while according to gender the proportion is 2/3 due to the predominance of the use of polyethylene bags between men and women, a practice considered as adequate.

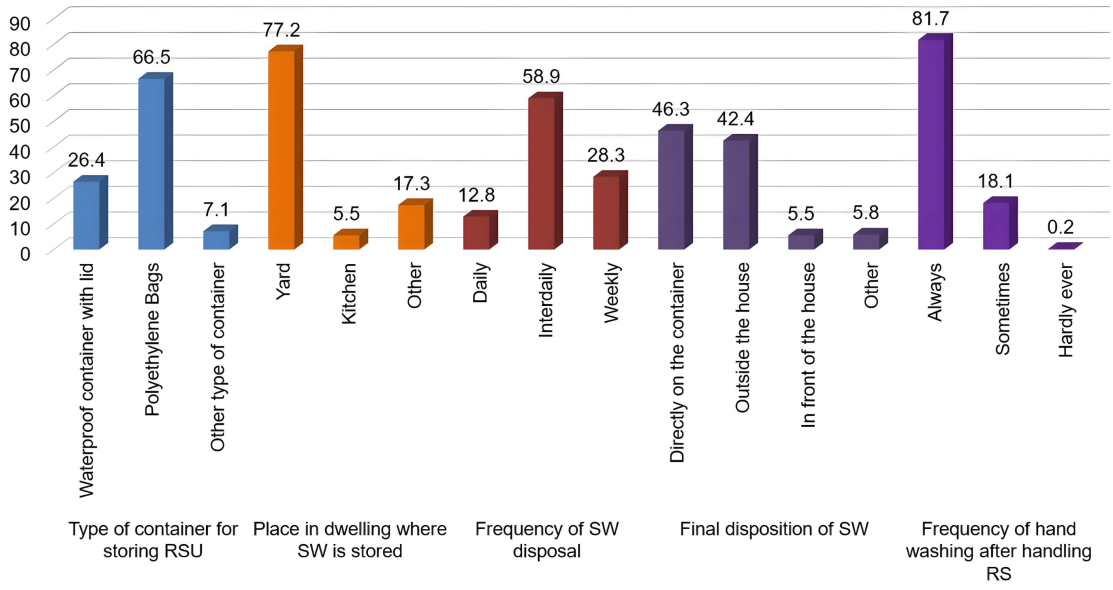

Figure 3. Population environmental practice on solid waste disposal by dimensions and categories of analysis

- Relative homogeneity in the population by educational level and gender is presented, with respect to the courtyard of the house where they store solid waste, thus avoiding the proliferation of animals and odor in the house.
- The periodicity of solid waste disposal in about half of the families of the different levels of education and gender is every other day, which is conditioned by the recurrence of the collecting units of the municipal government.
- The final disposal of solid waste that families carry out mainly in the collective deposit outside the house and complementarily in the container directly, are good practices both in families of the various levels of education and gender.
- Handwashing after handling solid waste is adequate, since more than 80% of heads of household always perform it, both those of secondary and higher education, being similar in gender.

3.2.2 Access to safe water services in the home

The conditions of access to safe water services are noted in the source of water supply in the house, level of access and home distribution of water, installed and operational hygienic services (Figure 4):

- The main source of water supply in the population's housing units is through a public network (94.77 per cent), while less than 5 per cent of housing units, located mainly in urban slums, are provided by a well or a public pool.
- 98% of the population has access to and distribution of safe water at home, of which 65.97% have access per hour per day, while only 1/3 of the houses have permanent water.
- The situation of home hygiene services in general in more than 97 per cent of the population is in a condition of installed and operational.

The conditions of access to safe water services show different characteristics considering the level of education and gender (Table 3):

- The source of water supply in the population's dwellings indicates that although it is predominant (more than 90%) access through public network is relatively greater in dwellings of family heads of higher education and in women.

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- The main form of household access and distribution of safe water in both educational level and gender is permanently or in hours per day, which will have a positive effect on the health and hygiene of family members.
- Hygienic services of families, predominantly (9 out of 10) are installed and operational, being relatively higher in heads of families of secondary and higher education and in women, affecting the preservation of good health of family members.

Consequently, an important aspect of access to basic family services is related to the coverage of the service provided by the Environmental Sanitation Company of Puno.

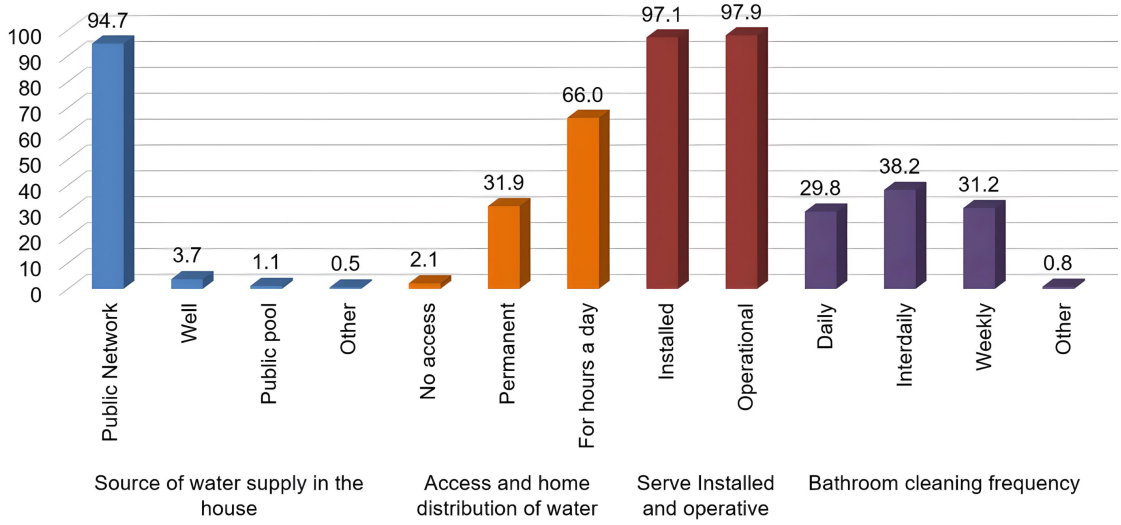

Figure 4. Conditions of access to water services in housing by size and analysis categories

3.2.3 Sanitation and hygiene practices of the population

Sanitation and hygiene conditions of family members are related to the way of storing water at home, actions to disinfect drinking water in the home, container where drinking water is stored, place of disposal of feces and frequency of cleaning the bathroom (Figure 5):

- The form of water storage in households is varied and diversified: on the one hand, about half of families deposit water properly in polyethylene tanks (44.2%) or cement tanks (5.0%); while more than half store in inadequate containers, such as plastic buckets (18.8%), buckets (24.6%) or cylinders (7.3%).
- As for the practice of disinfecting drinking water, most families (81.7%) boil it and only less than 1/6 of families boil it, disinfect and filter it.
- The practice of most urban families (91.1%) is that the container where drinking water is stored is kept blocked, while only nine out of every hundred families do not.
- In this context, good practice is widespread, mainly in home hygiene services (96.6%).
- The frequency of cleaning the bathroom is adequate in most families (68.3%), although it is most often done every other day (38.2%) and daily (30.1%), which is considered an ideal environmental practice. The frequency of cleaning of the bathroom indicates that families make it proportionally between daily, interdaily and weekly. The latter being an inadequate practice, due to the risks to the proliferation of infectious foci within the house.

The health and hygiene practices of the urban population of Puno according to educational level and

gender presents the following characteristics (Table 4):

- The form of home water storage according to the level of education indicates that most of the upper level (52%) and men (48.2%) have good practices because they use the polyethylene tank as a form of water storage.
- The sanitary practice of boiling drinking water characterizes most families at different levels of education, as well as men and women.
- More than 90 per cent of household feces are disposed of in the bathrooms of their homes, both at the level of education and gender. On the contrary, there is a small proportion who dispose their feces in the open air (1.3%) or in Titicaca Lake (1.8%), which is a practice that threatens the environment and human health.
- Regarding the frequency of cleaning of the bathroom, it is acceptable in most families of the various levels of education and gender situation, as they are performed daily or interdaily, having a positive impact on the preservation of the health and hygiene of the family.

Consequently, the study based on environmental regulations, shows that only 44.8% of the population performs adequate environmental practices in terms of disposal of urban solid waste, 64.1% in conditions of availability and access to water services and 62.2% in health and hygiene practices at home, showing the precariousness of the environmental awareness of the population, limited coverage and precariousness of environmental actions of the local and regional government. The sustained improvement of the pro-environmental behavior of the population demands the implementation of a new public policy of environmental education under the joint responsibility of the regional environmental institutions, the educational sector, and the academy.

3.3 Relationship between environmental attitudes and practices of the urban population of Puno

The relationship between environmental attitudes and practices of the urban population of Puno on environmental management of the family at home, access to water services and sanitation and hygiene conditions at home, is established to two dimensions:

- At a general level, due to a significance degree calculated from the chi-square test equal to 0.000, lower than the alpha significance level of 0.05 (5%). The study reveals the statistical evidence of the association and direction of a linear relationship between both analytical categories, but proportionally shows relative difference between them, since most of the population (62%) has a positive attitude, contrary, most of the population (55.2%) has inadequate environmental practices, showing a difference of 18 percentage points between them (Table 5).

- At the specific level, the following references are made by establishing the relationship between attitudes and the variables of the dimensions of the practices. In the variables of family practices at home and access to water services at home, according to statistical evidence (chi-square test), the study shows that there is no level of correlation; on the other hand, with the dimension of health and hygiene conditions of the family at home, the correlation level only presents with the variables of the form of storage of water at home and the disinfection of drinking water. The correlation level between environmental attitudes and practices also presents if the variables of spatial location of housing in the environment of Titicaca Lake, occupation and educational level are considered, but not with the variable gender situation.

Consequently, regarding the relationship between environmental attitudes and practices, the study shows that positive attitudes in most of the population do not necessarily translate into adequate environmental behaviors, a situation that questions the precariousness of the environmental consciousness of the population and the action of local and regional environmental institutions.

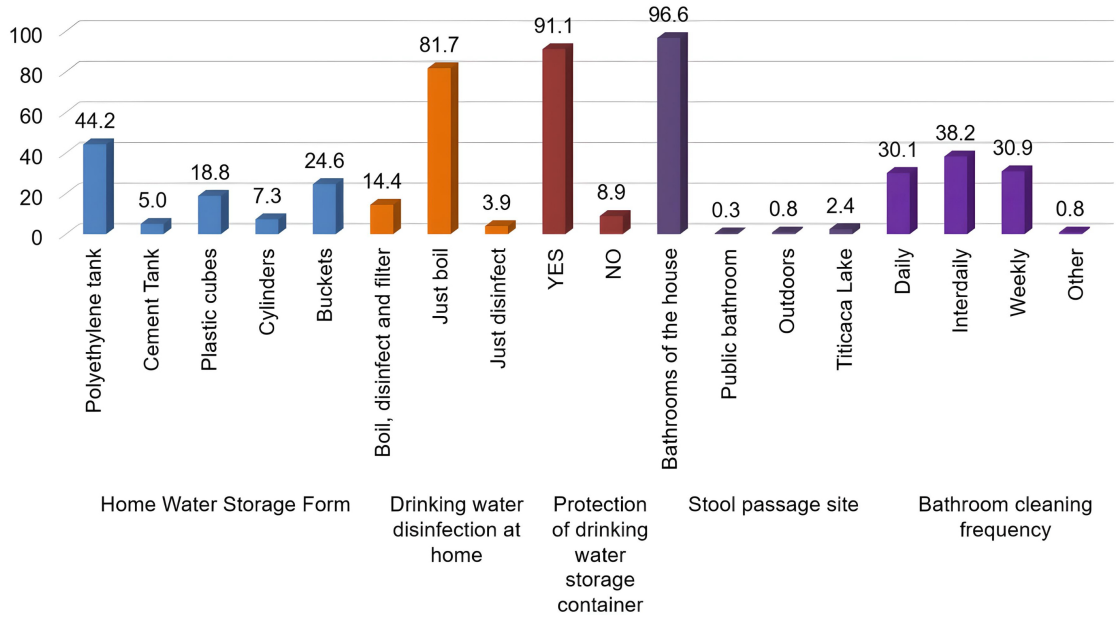

Figure 5. Sanitation and hygiene practices of the urban population of Puno by dimensions and categories of analysis

4 Discussion y Conclusions

The results of the study based on environmental regulations referred to the regulation of institutional and individual actions in the matter, valuation criteria and statistical evidence, allow concluding that the environmental attitudes of most of the population are positive, especially in terms of recognition of the factors of pollution at home, sources of pollution of the Titicaca Lake and negative effects on human health; conversely, the pro-environmental practices are inadequate, mainly in terms of environmental management at home and health and hygiene practices at home; thus indicating the existence of a relative discordance between the pro-environmental attitudes and the dimensions of the pro-environmental practices of the urban population of Puno, which is conditioned by the level of education and gender established by the units of analysis.

4.1 Environmental Concerns

The study, based on current environmental regulations, indicates that most of the urban population (6 out of 10 inhabitants) have a positive assessment of pollution factors at home and pollution sources at the Titicaca Lake and its correlation in effects on human health, showing the sense of co-responsibility of the population and the local government.

These results are relatively consistent with the findings of Estrada et al. (2021) where higher education students from Madre de Dios-Peru show moderate environmental concern associated with sociodemographic variables (gender, age, and educational level). In Mexico, Cantú (2020) shows that despite the similarities between gender, women have more environmental awareness than men; while Pérez-Franco et al. (2018) find a moderately positive attitude towards the environment in high school students from Murcia, with gender differences; or the hope of improvement in the future as the ROSE project points out (Vázquez and Manassero, 2008).

Conversely, Vargas et al. (2019) say that the level of environmental attitudes of 69% of Mexican university students is unacceptable, being worse in areas related to safety, health and environment. Andrade Salazar and Gonzales Portillo (2019) show that the precariousness of environmental knowledge hinders the formation of attitude and robust environmental awareness; whereas Moreno et al. (2019) refer that the environmental is not a priority for university students of Buenos Aires and Paraná, but the socioeconomic emergencies. This situation shows that environmental attitudes have a complex and contradictory nature, reason for which favora-

ble behaviors are gradually decreasing during the last two decades in the 33 European countries studied, without finding an objective reason for such reduction (Franzen and Vogl, 2013).

Likewise, it is argued that the analysis of human-nature relationships in different cultural contexts cannot be approached from a one-dimensional perspective, as has been implied by traditional measures of environmental attitudes and concern for the environment (Amérigo et al., 2012) rather, it presents evidence of the need to consider multidimensional approaches, such as Thompson and Barton (1994) which measures the environmental orientation of behavior and Schultz (2001) which establishes the assessment of the impact of the environment on different objects.

4.2 Pro-environmental behaviors

The study concludes that about half of the urban population has inadequate environmental practices regarding environmental management at home, access to water services and sanitation and hygiene practices at home, denoting not only the precariousness of the environmental awareness of the population, but also the limited coverage and ineffectiveness of environmental promotion actions implemented by the local government and regional environmental institutionalism.

On pro-environmental behavior, Sandoval et al. (2019) in Colombia show that university students have positive environmental beliefs and attitudes in most of the dimensions, while Vilca et al. (2021) say that university students from Juliaca-Peru have two emerging behavioral structures that describe the pro-environmental behavior of avoidant actions (reducing waste, saving energy and water) or beneficial (recycling, reuse and segregation). On the other hand, Hernández et al. (2001) identify inconsistencies in the actions of the staff of protected wild area of Costa Rica, since they prefer to purchase disposable and packaged products and use paper only on one side, but they express a behavior favorable to saving water and energy, as well as the separation of plastic, aluminum and paper. Faced with this situation or dual behavior, Berenguer and Corraliza (2000) argue that there is no single model for predicting environmental behavior, and that people have trouble acting on behalf of the environment despite recognizing the severity of the problems (Moreno et al., 2005).

4.3 Relationship between environmental concerns and behaviors

The results of the study show that positive environmental concerns are not correlated towards adequate environmental behaviors, denoting not only the precariousness of the environmental awareness of the population, but also the sense of co-responsibility of limited coverage and ineffectiveness of environmental promotion actions implemented by the local government and regional environmental institutionalism.

This situation is corroborated by Rivera-Jacinto and Rodríguez-Ulloa (2009) who show that university students in the north of the country, even though they have positive environmental attitudes, do not necessarily have adequate environmental behaviors. While Bernedo Berríos and Cazorla Galdos (2020), in a study conducted in Tacna-Peru, shows that there is a direct and significant relationship (Spearman's Rho=0.614 and p=0.000) between environmental concern and ecological behavior of students. Similarly, (Suárez et al., 2007) in Mexico point out the existence of a significant relationship between environmental attitudes and motivation to act pro-environmentally; Favara and Moreno (2020) argue that older adults with higher emotional affinity (emotional relationship with nature) and more connection (interest in nature to know and be in contact with it) are more likely to engage in pro-environmental behaviors. However, Álvarez and Vega (2009) say that environmental attitudes and behaviors have very low correlations, although attitudes have a great influence on behavior if other factors do not prevent it from materializing.

In Spain, Amérigo et al. (2012); Amérigo and García (2014) in the analysis of the relationship between environmental attitudes and behaviors, found predictors of pro-environmental behavior, as well as Murga (2008); Vázquez and Manassero (2009) who argue that the environmental attitudes of young people are positive, but with some pessimistic aspect, since the willingness to act in favor of the environment (ecological behavior) is low in relation to the concern shown. In addition, (Palavecinos et al.,

2016) argue that the structure of environmental attitudes and concern among students from Chile and Spain are similar, with the same dimensions and types of behavior, as well as in the human behavior of young people who have a higher priority because attitudes are easy to modify or adapt (Pérez-Franco et al., 2018).

For the sustainable improvement of environmental attitudes and behaviors of social and institutional actors, it is necessary to design a new public policy for capacity-building in environmental and ecological education, whose implementation, under the leadership of local and regional environmental institutions, incorporates the effective participation of civil society based on a system of incentives. Hence, it is essential to consider the proposals made in the Latin American context: the edu-communication for sustainable development (Rendón et al., 2018); the photographic record (Perdomo Báez et al., 2018); the game or board games (Sanabria et al., 2017); environmental education with an integrative and interdisciplinary approach (Paula et al., 2019; Álvarez and Vega, 2009); educating with ethics and environmental values (de Castro et al., 2009). On the other hand, in the face of the increasing pollution process of Titicaca Lake due to the poor management of RSU and wastewater and the collapse of oxidation ponds and their effects on human health and the environment, it is important to consider the actions and proposals that are being carried out: the strategy of recycling before discarding (Aliaga Ortega, 2017); solid waste management actions (Olaguez et al., 2019); the participatory-action-research strategy (Rodríguez et al., 2018); co-responsibility of civil society organizations at some stages of the MRSU (De Cármen et al., 2019). In short, these proposals, strategies or methodological frameworks, subjected to a critical analysis must be validated in accordance with the Andean socio-cultural context and the Puno plateau.

Author Contributions

JETQ; Conceptualization, research, formal analysis, methodology, validation, visualization, preparation, creation and presentation of the work, writing the original draft and the final version of the manuscript.

References

Agenda 21 (1992). Programa de naciones unidas (onu) para promover el desarrollo sostenible. Departamento de Asuntos Económicos y Sociales - División de Desarrollo Sostenible . Online:https://n9.cl/bdm9a .

Aliaga Ortega, W. (2017). Incidencia de gestión ambiental con la contaminación por residuos sólidos de la bahía interior del lago titicaca puno. *Revista Científica Investigación Andina*, 16(2):67–79. Online:https://n9.cl/2giwk.

Álvarez, P. and Vega, P. (2009). Actitudes ambientales y conductas sostenibles: implicados para la educación ambiental. *Revista de Psicodidáctica*, 14(2):245–260. Online:https://n9.cl/u6eht.

Amérigo, M., Aragonés, J., and García, J. (2012). Explorando las dimensiones de la preocupación ambiental. una propuesta integradora. *PsyEcology*, 3(3):299–311. Online:https://n9.cl/lt3sf.

Amérigo, M., Aragonés, J., Sevillano, V., and Cortés, B. (2005). La estructura de las creencias sobre la problemática medioambiental. *Psicothema*, 17(2):257–262. Online:https://n9.cl/msl9v.

Amérigo, M. and García, J. (2014). Perspectiva multidimensional de la preocupación por el medio ambiente. relación entre dimensiones actitudinales y comportamientos. *Psico*, 45(3):406–414. Online:https://n9.cl/3h9fb.

Amérigo, M., García, J., and Cortes, P. (2017). Análisis de actitudes y conductas pro-ambientales: un estudio exploratorio con una muestra de estudiantes universitarios brasileños. *Ambiente & Sociedade*, 20:01–20. Online:https://n9.cl/kttmc.

Andrade Salazar, J. and Gonzales Portillo, J. (2019). Relación entre actitudes pro-ambientales y conocimientos ecológicos en adolescentes con relación al entorno rural o urbano que habitan. *Revista Kavilando*, 11(1):105–118. Online:https://n9.cl/3ft1u.

Aranibar Ramos, E. and Patiño Huayhua, A. (2022). Turismo, camino hacia la sostenibilidad: una aproximación al lago titicaca peruano. *Revista de Ciencias Humanísticas y Sociales (ReHuSo)*, 7(3):46–62. Online:https://n9.cl/e4mve.

Berenguer, J. and Corraliza, J. (2000). Preocupación ambiental y comportamientos ecológicos. *Psicothema*, 12(3):325–329. Online:https://n9.cl/doiutq.

Bernedo Berríos, S. and Cazorla Galdos, J. (2020). Preocupación ambiental y su relación con la conducta ecológica en estudiantes de ingeniería de la universidad privada de tacna. *Ingeniería Investiga*, 2(2):418–430. Online:https://n9.cl/1gkbe.

Cantú, P. (2020). Preocupación y deterioro de la calidad ambiental. apreciación de los estudiantes universitarios. *Ambiente y desarrollo*, 24(46):24–26. Online:https://n9.cl/7t5y0.

Clayton, S. (2003). *The Psychological Significance of Nature*, chapter Environmental Identity: A Conceptual and an Operational Definition, page 45–65. The MIT Press.

De Cármen, V., Rodríguez, A., Juárez, A., Sampedro, M., Reyes, M., and Silva, S. (2019). La importancia de la participación y corresponsabilidad en el manejo de los residuos sólidos urbanos. *Acta universitaria*, 29:1–16. Online:https://n9.cl/leysl.

de Castro, A., Cruz, J., and Ruiz, L. (2009). Educar con ética y valores ambientales para conservar la naturaleza. *Convergencia*, 16(50):353–382. Online:https://n9.cl/dhmi80.

Dunlap, R., Van Liere, K., Mertig, A., and Jones, R. (2000). New trends in measuring environmental attitudes: measuring endorsement of the new ecological paradigm: a revised nep scale. *Journal of social issues*, 56(3):425–442. Online:https://n9.cl/fb81c.

Estrada, E., Huaypar, K., Mamani, H., Velásquez, L., and Gallegos, N. (2021). La preocupación ambiental en estudiantes de educación superior de madre de dios, perú. *Ciencia Amazónica (Iquitos)*, 9(1):111–122. Online:https://n9.cl/b9mjl.

Favara, J. and Moreno, J. (2020). Preocupación ambiental y conductas proambientales en jóvenes y adultos mayores. *Revista de psicología (Santiago)*, 29(1):80–89. Online:https://n9.cl/8o6wp.

Flores, E., Miranda, M., and Villasís, M. (2017). El protocolo de investigación vi: cómo elegir la prueba estadística adecuada. estadística inferencial. *Revista Alergia México*, 64(3):364–370. Online:https://n9.cl/lxfyi.

Fontúrbel-Rada, F. (2003). Algunos criterios biológicos sobre el proceso de eutrofización a orillas de seis localidades del lago titikaka. *Ecología aplicada*, 2(1):75–79. Online:https://n9.cl/d7qex.

Franzen, A. and Vogl, D. (2013). Two decades of measuring environmental attitudes: A comparative analysis of 33 countries. *Global Environmental Change*, 23(5):1001–1008. Online:https://n9.cl/03svmk.

Hernández, B., Corral, V., Hess, S., and Suárez, E. (2001). Sistemas de creencias ambientales: un análisis multi-muestra de estructuras factoriales. *Estudios de psicología*, 22(1):53–64. Online:https://n9.cl/kksoj.

Instituto Nacional de Estadística e Informática (2018). *Anuario de Estadísticas Ambientales 2018*. Online:https://n9.cl/zx36d.

Jimenez, L., Jahuira, F., and Ibañez, V. (2016). Tratamiento de aguas eutrofizadas de la bahía interior de puno, perú, con el uso de dos macrófitas. *Revista de Investigaciones Altoandinas*, 18(4):403–410. Online:https://n9.cl/92oit.

Kals, E., Schumacher, D., and Montada, L. (1999). Emotional affinity toward nature as a motivational basis to protect nature. *Environment and behavior*, 31(2):178–202. Online:https://n9.cl/zug1r6.

Luca, E. and Ticona, B. (2006). *La contaminación del lago Titicaca y el turismo*. PhD thesis, Escuela Postgrado UNA Puno.

Milfont, T. and Duckitt, J. (2010). The environmental attitudes inventory: A valid and reliable measure to assess the structure of environmental attitudes. *Journal of environmental psychology*, 30(1):80–94. Online:https://n9.cl/ckb3u.

Miranda Aliaga, A. (2004). Efectos de la contaminación de la bahía interior de puno en la salud humana, 2003. *Revista Científico Social*, 1(1).

Moreno, J., Rodriguez, L., and Favara, J. (2019). Conciencia ambiental en estudiantes universitarios. un estudio de la jerarquización de los ods. *Rev. de Psicología*, 30(1):113–119 . Online:https://n9.cl/x2u1fi.

Moreno, M., Corraliza, J., and Ruiz, J. (2005). Escala de actitudes ambientales hacia problemas específicos. *Psicothema*, 17(3):502–508. Online:https://n9.cl/dhsas.

Murga, M. (2008). Percepciones, valores y actitudes ante el desarrollo sostenible. detección de necesidades educativas en estudiantes universitarios. *Revista española de pedagogía*, 66(240):327–343. Online:https://n9.cl/o72qyr.

Olaguez, E., Espino, P., Acosta, K., and Méndez, A. (2019). Plan de acción a partir de la percepción en estudiantes de la universidad politécnica de sinaloa ante el reciclaje de residuos sólidos y la educación ambiental. *Formación universitaria*, 12(3):3–14. Online:https://n9.cl/a4bzl.

Palavecinos, M., Amérigo, M., Ulloa, J., and Muñoz, J. (2016). Preocupación y conducta ecológica responsable en estudiantes universitarios: estudio comparativo entre estudiantes chilenos y españoles. *Psychosocial Intervention*, 25(3):143–148. Online:https://n9.cl/b2nh8.

Paula, C., Pérez, J., and Sierra, J. (2019). La educación ambiental con enfoque integrador. una experiencia en la formación inicial de profesores de matemática y física. *Revista Electrónica Educare*, 23(1):181–202. Online:https://n9.cl/13u7p.

Perdomo Báez, O., Salazar Báez, P., and Fernádez, L. (2018). Avifauna local: una herramienta para la conservación, el ecoturismo y la educación ambiental. *Ciencia en Desarrollo*, 9(2):17–34. Online:https://n9.cl/0jf3m.

Pérez-Franco, D., de Pro-Bueno, A., and Pérez-Manzano, A. (2018). Actitudes ambientales al final de la eso. *Un estudio diagnóstico con alumnos de Secundaria de la Región de Murcia. Rev. Eureka Sobre Enseñ. Divulg. Las Cienc*, 15:1–15. Online:https://n9.cl/5uko.

Rendón, L., Escobar, J., Arango, A., Molina, J., Villamil, T., and Valencia, D. (2018). Educación para el desarrollo sostenible: acercamientos desde una perspectiva colombiana. *Producción+ Limpia*, 13(2):133–149. Online:https://n9.cl/3iw3t.

Ritchey, F. (2002). *Econometric Analysis*. McGraw-Hill.

Rivera-Jacinto, M. and Rodríguez-Ulloa, C. (2009). Actitudes y comportamientos ambientales en estudiantes de enfermería de una universidad pública del norte del perú. *Revista Peruana de Medicina Experimental y Salud Pública*, 26(3):338–342. Online:https://n9.cl/95ncyn.

Rodríguez, A., Fontalvo, I., Colón, N., Rodríguez, W., Suarez, V., and Muñoz, Y. (2018). Sensibilización en el manejo de residuos sólidos mediante la investigación-acción participativa. *Módulo Arquitectura-CUC*, 20(1):29–38. Online:https://n9.cl/ue33b.

Sanabria, I., Sandoval, L., and Arango, A. (2017). El juego como estrategia para la enseñanza y el aprendizaje de la evolución biológica en estudiantes de noveno grado. *Bio-grafía*, 10(19):146–152. Online:https://n9.cl/7ambk.

Sandoval, M., Páramo, P., Orejuela, J., González, I., Cortés, O., Herrera, K., Garzón, C., and Erazo, C. (2019). Paradojas del comportamiento proambiental de los estudiantes universitarios en diferentes disciplinas académicas. *Interdisciplinaria*, 36(2):165–184. Online:https://n9.cl/62hgy.

Schultz, P. (2001). The structure of environmental concern: Concern for self, other people, and the biosphere. *Journal of environmental psychology*, 21(4):327–339. Online:https://n9.cl/1vtb6.

Suárez, E., Salazar, M., Hernández, B., and Martín, A. (2007). ¿qué motiva la valoración del medio ambiente? la relación del ecocentrismo y del antropocentrismo con la motivación interna y externa. *Revista de Psicología social*, 22(3):235–243. Online:https://n9.cl/q8um7.

Thompson, S. and Barton, M. (1994). Ecocentric and anthropocentric attitudes toward the environment. *Journal of environmental Psychology*, 14(2):149–157. Online:https://n9.cl/ztzoll.

Tumi Quispe, J. (2014). Representaciones sociales de la población de la ciudad de puno sobre gestión de residuos sólidos. *Revista de Investigaciones Altoandinas-Journal of High Andean Research*, 16(01):59–74. Online:https://n9.cl/0jos7.

Tumi Quispe, J. (2016). Actitudes y prácticas ambientales de la población de la ciudad del puno, perú sobre gestión de residius sólidos. *Espacio abierto: cuaderno venezolano de sociología*, 25(4):267–285. Online:https://n9.cl/lhlgp.

Valderrama, A. and Canales, A. (2007). Impacto del manejo de residuos sólidos sobre la salud familiar en la bahía de la ciudad de puno. *Revista Investigación*, 3(3).

Vargas, C., Martínez, M., and Fernández, M. (2019). Actitudes ambientales en los estudiantes de nivel superior en méxico. *Luna Azul*, 15(35):45–49. Online:https://n9.cl/m6vhv.

Vázquez, Á. and Manassero, M. (2008). El declive de las actitudes hacia la ciencia de los estudiantes: un indicador inquietante para la educación científica. *Revista Eureka sobre Enseñanza y Divulgación de las ciencias*, 5(3):274–292. Online:https://n9.cl/bthkxq.

Vázquez, A. and Manassero, M. (2009). La relevancia de la educación científica: actitudes y valores de los estudiantes relacionados con la ciencia y la tecnología. *Enseñanza de las ciencias: revista de investigación y experiencias didácticas*, 27(1):33–48. Online:https://n9.cl/s7e9v.

Velásquez Patiño, A. (2008). La gestión de los residuos sólidos urbanos en la ciudad de hannover: un modelo exitoso. *Anales de geografía de la Universidad Complutense*, 28(1):163–177. Online:https://n9.cl/92as6.

Vilca, G., López, P., Gallegos, S., and López, M. (2021). Comportamiento proambiental en una muestra cualitativa de estudiantes universitarios de juliaca-perú. *Revista Científica de la UCSA*, 8(2):39–50. Online:https://n9.cl/3if71.

Vining, J., Merrick, M., and Price, E. (2008). The distinction between humans and nature: Human perceptions of connectedness to nature and elements of the natural and unnatural. *Human Ecology Review*, 15(1):1–11. Online:https://n9.cl/rmsaf.

World Health Organization (2019). *Estado Mundial del Saneamiento*. UNICEF-WHO. Online:https://n9.cl/9siaz.

Appendix

Table 1. Positive environmental attitude of the urban population of Puno by dimensions and categories of analysis and according to level of education and gender

Dimension	Variable	Positive attitude						
		Total		Degree of education (%)			Gender (%)	
		N°	%	Prim	Sec	Sup	Male	Female
Pollution factors at home	Water quality	356	93.2	95.0	93.9	92.7	91.7	94.7
	Garbage collection	338	88.5	100.0	90.0	86.7	86.0	91.0
	Unpaved streets	213	55.8	65.0	52.6	56.5	57.0	54.5
	Home animal	266	69.6	55.0	64.9	73.0	66.3	73.0
	Sewer obstruction	264	69.1	75.0	59.6	73.0	67.9	70.4
Sources of pollution of Titicaca lake	Wastewater	296	77.5	85.0	68.4	81.0	82.4	72.5
	Solid waste	217	56.8	75.0	45.6	60.5	60.1	53.4
	Oxidation lag collapse	322	84.3	100.0	82.5	83.9	86.5	82.0
Effects of pollution on human health	Neuro-psychological symptoms	267	69.9	60.0	53.5	78.2	74.6	65.1
	Digestive symptoms	253	66.4	50.0	51.8	74.5	69.8	63.0
	Dermatological symptoms	144	37.7	5.0	17.5	49.6	43.0	32.3
	Ocular symptoms	138	36.1	10.0	19.3	46.0	40.9	31.2

Source: Socio-environmental survey, Puno, 2018.

Table 2. Population environmental practice on solid waste disposal by educational level and gender

Variable	Category	Total		Instruction Grade			Gender	
		N°	%	Prim.	Sec.	Sup.	Male	Female
Type of container for storing RSU	Waterproof container with lid	101	26.4	0.0	25.4	29.0	25.4	27.5
	Polyethylene Bags	254	66.5	100.0	69.3	62.5	66.8	66.1
	Other type of container	27	7.1	0.0	5.3	8.5	7.8	6.3
Place in dwelling where SW is stored	Yard	295	77.2	80.0	75.4	77.4	78.2	75.7
	Kitchen	21	5.5	10.0	6.1	4.8	3.1	7.9
	Other	66	17.3	10.0	18.4	17.7	18.7	16.4
Frequency of SW disposal	Daily	49	12.8	10.0	12.3	13.7	15.5	10.6
	Interdaily	225	58.9	50.0	58.8	59.3	52.8	64.6
	Weekly	108	28.3	40.0	28.9	27.0	31.6	24.9
Final disposition of SW	Directly on the container	177	46.3	35.0	40.4	49.6	45.6	46.6
	Outside the house	162	42.4	50.0	53.5	37.1	39.9	45.5
	In front of the house	21	5.5	10.0	4.4	5.6	6.7	4.2
	Other	22	5.8	5.0	1.8	7.7	7.8	3.7
Frequency of hand washing after handling RS	Always	312	81.7	60.0	82.5	83.1	80.8	82.5
	Sometimes	69	18.1	35.0	17.5	16.9	18.7	17.5
	Hardly ever	1	0.2	5.0	0.0	0.0	0.5	0.0

Source: Socio-environmental survey, Puno, 2018.

Table 3. Conditions of access to water services in housing by educational level and gender

Variable	Category	Total		Instruction Grade			Gender	
		N°	%	Prim.	Sec.	Sup.	Male	Female
Source of water supply in the house	Public Network	362	94.7	90.0	93.0	96.0	92.7	96.8
	Well	14	3.7	10.0	4.4	2.8	4.7	2.6
	Public pool	4	1.1	0.0	1.8	0.8	2.1	0.0
	Other	2	0.5	0.0	0.9	0.4	0.5	0.5
Access and home distribution of water	No access	8	2.1	30.0	28.9	33.9	33.2	31.2
	Permanent	122	31.9	65.0	69.3	64.1	62.7	68.8
	For hours a day	252	66.0	5.0	1.8	2.0	4.19	0.0
Serve installed and operative	Installed	371	97.1	95.0	97.4	97.2	95.9	98.4
	Operational	374	97.9	95.0	98.0	98.0	96.4	99.5

Source: Socio-environmental survey, Puno, 2018.

Table 4. Health and hygiene practices of the urban population of Puno according to educational level and gender

Variable	Category	Total		Degree of education (%)			Gender (%)	
		N°	%	Prim	Sec	Sup.	Male	Female
Home Water Storage Form	Polyethylene tank	169	44.2	10.0	33.3	52.0	48.2	40.2
	Cement Tank	19	5.0	5.0	1.8	6,5	3.6	6.3
	Plastic cubes	72	18.8	35.0	31.6	11.7	21.2	16.4
	Cylinders	28	7.3	10.0	5.3	8.1	7.3	7.4
	Buckets	94	24.6	40.0	28.1	21.8	19.7	29.6
Drinking water disinfection at home	Boil, disinfect and filter	55	14.4	0.0	8.8	18.1	18.1	10.6
	Just boil	312	81.7	95.0	90.4	76.6	76.7	86.8
	Just disinfect	15	3.9	5.0	0.9	5.2	5.2	2.6
Protection of drinking water storage container	YES	348	91.1	95.0	91.2	90.7	92.7	89.4
	NO	34	8.9	5.0	8.8	9.3	7.3	10.6
Stool passage site	Bathrooms of the house	369	96.6	90.0	98.2	99.6	98.4	98.9
	Public bathroom	1	0.3	0.0	0.0	0.4	0.5	0.0
	Outdoors	3	0.8	5.0	0.0	0.0	0.5	0.0
	Titicaca Lake	9	2.4	5.0	1.8	0.0	0.5	1.1
Bathroom cleaning frecuency	Daily	115	30.1	5.0	19.3	37.1	32.6	27.5
	Interdaily	146	38.2	50.0	55.3	29.4	36.3	40.2
	Weekly	118	30.9	40.0	25.4	32.7	29.5	32.3
	Other	3	0.8	5.0	0.0	0.8	1.6	0.0

Source: Socio-environmental survey, Puno, 2018.

Table 5. Assessment of environmental attitudes and practices of the population (frequency distribution and correlation analysis).

Frequency distribution					
Valuation		**Frequency**	**Percentage**	**Percent valid**	**Cumulative Percent**
ATTITUDES	Positive	237	62.0	62.0	62.0
	Negative	145	38.0	38.0	100.0
PRACTICES	Adequate	171	44.8	44.8	44.8
	Inadequate	211	55.2	55.2	100.0
	Total	**382**	**100.0**	**100.0**	

Dimensions and variables of analysis of the environmental practices of the population				
Independent Variables	**Value**	**GL**	**Asymptotic Sig (2-sided)**	**Question**
Family Environmental Practices at Home [PAF]				
SW Storage Vessel Type	5.573	2	0.062	23
Place of trash storage	3.377	2	0.185	24
Periodicity of solid waste disposal	3.390	2	0.213	25
Final disposal of solid waste	1.183	3	0.757	26
Frequency washing hands after handling SW	2.351	2	0.309	28
Conditions of access to water services [ASH]				
Source of water supply at home	2.111	3	0.550	29
Degree of access and distribution of safe water	3.899	2	0.142	33
Installation of hygienic services at home	0.549	1	0.459	34
Operating Hygienic Services at home	0.583	1	0.445	35
Home Health and Hygiene Practices [PSH]				
Form of water storage at home	20.635	4	0.000	30
Disinfection actions of drinking water at home	29.257	2	0.000	31
Lid storage containers of drinking water	1.158	1	0.282	32
Stool passage site	2.274	3	0.518	27
Cleaning frequency of the bathroom	11.565	3	0.009	36
Location and socioeconomic status				
Spatial location of the dwelling	89.869	3	0.000	38
Economic Status (Occupation)	52.562	5	0.000	7
Social status (Educational level)	44.536	2	0.000	5
Gender	5.637	1	0.018	4

Source: Socioenvironmental Survey, Puno 2018.

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Sustainable Development

A hydropower development perspective in Ecuador: Past, present, and future

Una perspectiva del desarrollo hidroeléctrico en Ecuador: pasado, presente y futuro

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Abstract

Ecuador is a small Andean country located in the western hemisphere of South America. The country has $361,747 hm^3$ annual superficial water resources; As a result, Ecuador, in the last fifteen years (2005 to 2020), has been rapidly developing hydropower projects to triple the production in this renewable source. There were eight new hydroelectric plants constructed in Ecuador among 2007 and 2015 invested close to USD 6 billion the projects. Increased the energy response with renewables; for example, in 1985, the country produced 4 TWh, in 2005-registered 7 TWh, and to 2020, 24 TWh. According to the Electricity Corporation of Ecuador in 2020 reported that generated around 80% of all electricity through hydropower; thus, the article aims to critically analyze the development of hydropower in Ecuador in recent years and establish general energy projections to 2030 to expand the fields of knowledge and perspectives. The paper methodology is quantitative, according to scientific editorial sources, articles, investigative documents, and collects data from government agencies that regulate energy development in Ecuador. It is conclusive between a projection's calculation, Ecuador will need for the year 2030 around 43 TWh, 47 TWh, or 52 TWh to supply the energy grid, according to the scenarios proposed (low, medium, high). Although hydropower will be essential to contribute to this requirement, the country has a barrier because hydropower is very sensitive to external factors of diverse nature, generating an uncertainly future directly associated with climatic effects.

Keywords: Ecuador, renewable energies, hydropower development, perspective, projections.

Resumen

Ecuador es un pequeño país andino ubicado en el hemisferio occidental de América del Sur. El país cuenta con 361.747 hm^3 anuales de recursos hídricos superficiales. Como resultado, Ecuador, en los últimos quince años (2005 a 2020), ha estado desarrollando proyectos hidroeléctricos para triplicar la producción en esta fuente renovable. Hubo ocho nuevas centrales hidroeléctricas construidas en Ecuador entre 2007 y 2015, en donde se invirtieron cerca de USD 6 mil millones en los proyectos, lo que incrementó la respuesta energética con renovables; por ejemplo, en 1985 el país produjo 4 TWh, en 2005 registró 7 TWh y hasta 2020, 24 TWh. Según la Corporación de Electricidad del Ecuador en 2020 informó que generó alrededor del 80 % de toda la electricidad a través de hidroelectricidad. Así, el artículo tiene como objetivo analizar críticamente el desarrollo de la energía hidroeléctrica en Ecuador en los últimos años y establecer proyecciones energéticas generales al 2030 para ampliar los campos de conocimiento y perspectivas. La metodología del trabajo es cuantitativa, de acuerdo con fuentes editoriales científicas, artículos, documentos de investigación, y recolecta datos de agencias gubernamentales que regulan el desarrollo energético en Ecuador. Se concluye que, mediante un cálculo de proyecciones, Ecuador necesitará para el año 2030 alrededor de 43 TWh, 47 TWh o 52 TWh para abastecer la red energética, según los escenarios propuestos (bajo, medio, alto). Si bien la energía hidroeléctrica será fundamental para contribuir a este requerimiento, el país tiene una barrera porque la energía hidroeléctrica es muy sensible a factores externos de diversa índole, generando un futuro incierto directamente asociado a los efectos climáticos.

Palabras clave: Ecuador, energías renovables, desarrollo hidroeléctrico, perspectiva, proyecciones.

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1 Introduction

Ecuador is a small Andean country located in the western hemisphere, northwest of South America, composed of three main regions: Coast, Sierra, and Amazon (Ministerio de Medio Ambiente, Agua y Transición ecológica, 2019). The country characterizes by a unique topography, climatic zones diversity, and a prolific population of animal species. According to the Ecuadorian Ministry of the Environment and Water (MAATE, acronym named in Spanish), biological wealth is reflected in a wide array of organisms, and 10% of species of vascular projects in the biosphere are found in a zone that barely represents 2% of the global surface (Guilcatoma-Aimacaña, 2010; Mena-Vasconez, 2018). The country has 376.018 hm^3 of annual water resources, of which 361.747 hm^3 are superficial while the rest are underground (Hasan and Wyseure, 2018). In addition, the yearly average volume for the regions of the country, Coast, Sierra, and Amazon is 70.046 hm^3, 59.725 hm^3, and 246.246 hm^3, respectively (CISPDR and SENAGUA, 2016).

Moreover, with the availability of surface water resources, Ecuador has been rapidly developing hydropower projects to triple the production in the last fifteen years (2005 to 2020), as indicated in Figure 5. In 1985 the country produced 4 TWh, and in 2005 it registered 7 TWh, and in 2020 24 TWh of hydropower. The Electricity Corporation of Ecuador (CELEC, acronym named in Spanish) in 2020 reported that the country generated around 80% of all energy through hydropower, so hydropower is a crucial source to meet the national demand (CELEC, 2020). On the other hand, there were eight new hydroelectric plants constructed in Ecuador among 2007 and 2015 invested close to USD 6 billion, doubling their capacity (Vaca-Jiménez et al., 2020). In 2017 it was inaugurated the Coca Codo Sinclair as the largest project with 1,500 MW capacity, which supplies 30% of energy nowadays in the country with all the generating turbines (Álvarez-Chiriboga, 2020; Hidalgo et al., 2024).

In addition, the International Renewable Energy Agency (IRENA) determines that the average evolution of installed capacity in the five years between 2016 and 2020 was 1.8% (IRENA, 2020). However, globally, a 2017 calculation estimated that only 22% of the hydropower potential and 4.2% of the remaining renewable energies are currently used (Turner et al., 2017). In addition, the potential for amplified

However, Ecuador is very sensitive to external factors of diverse nature such as floods, tsunamis, earthquakes, and extreme rains due to atmospheric components, geographical location, rugged orography, and prevailing meteorological characteristics that can cause severe impacts on the economy (Naranjo Silva et al., 2021; Purcell and Martínez, 2018). Nevertheless, climate change intensifies natural meteorological variability, affecting the hydropower installations (Álvarez-Chiriboga, 2020). At the end of the 80s, the analytical development paradigm inserted concerns about the environment and extended the interest in growth policies based on the quality and management of renewable sources (Tang et al., 2018). But the effects of these renewable sources are not too quantified and verified, generating a new significant problem to analyze (Jin et al., 2016).

Under this background, this article aims to critically analyze the hydropower development in Ecuador in recent years and establish the general energy projections up to 2030 to expand the fields of knowledge and discern the perspective of this renewable source carried out quickly in a developing country.

2 Hydropower in the world

According to the International Hydropower Association (IHA), the worldwide hydropower capacity was 1,330 GW in 2020 (International Hydropower Association, 2021). In addition, this renewable source in 2020 reported around 14,000 active projects in 180 countries (ICOLD, 2019; Llamosas and Sovacool, 2021). Furthermore, the report of IHA mentions that there was an increase of 21 GW in the total hydropower installed capacity in 2020, increasing 1.6% compared to 2019 (International Hydropower Association, 2021). Consistent with Killingtveit (2018), the hydropower development is expected to increase. Figure 1 establishes the average percentage growth tendency from 2007 to 2016 at around 3%.

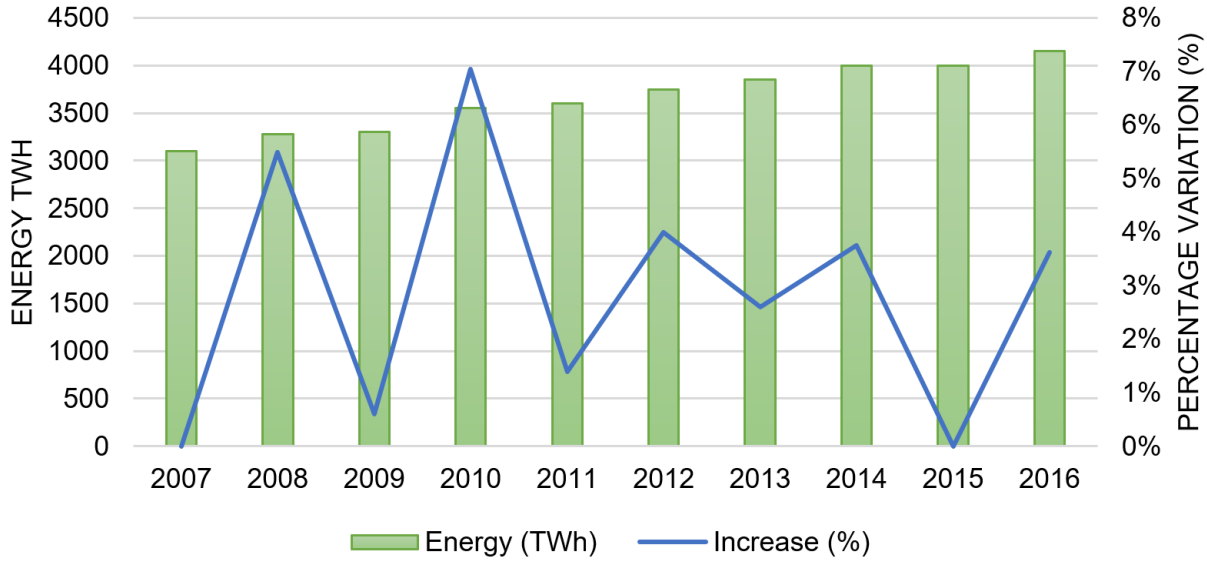

Figure 1. Global hydropower growth TWh period 2007- 2016.
Source: International Renewable Energy Agency (2020); Killingtveit (2018).

hydropower production is significant to meet an actual long-term deployment calculated at more than 8 000 TWh by 2050 (Schaefli, 2015).

With the global background, hydropower can be defined as a mature technology and the most widely used among renewables, although globally the share has slowly declined (Naranjo Silva and Álvarez, 2021). The global hydropower share fell from 72% in 2010 (881 GW) to 41% in 2020 (1,153 GW), excluding pumped-type hydropower despite the increase in installed capacity (IRENA, 2021). Currently, hydropower is substantial in most Latin American, Asian countries and Europe, but there are significant risks due to persistent inflows and water availability (Lu et al., 2020; Teräväinen, 2019).

3 Methodology

Numerous references were generated worldwide between protocols, manuals, and projections that leader or mitigate the hydropower impacts; therefore, in a world of technology and constant changes, there are reflections and approaches to each issue in a multi-diverse way. Therefore, the paper's proposed methodology is quantitative, evaluating the installed development of hydropower projects in Ecuador in recent years. In the quantitative part, simulations and projections are presented according to scientific editorial sources, articles, and investigative documents defined, looking for topics and aspects such as the hydropower development of Ecuador and energy policies. Thus, the valuable documents are listed based on issues that contribute to this paper; the databases analyzed are detailed in Table 1.

Table 1. Scientific editorial analyzed.

Period	Digital repositories	Selected articles
2016-2020	Science Direct	11
2016-2020	Springer	9
2016-2020	Taylor & Francis	8
	Total	28

Three digital repositories were selected (Science Direct, Springer and Taylor Francis) as they have more information associated to hydropower energy as the main topic of the present manuscript, and additionally the useful data was covering a specific period of time (2016-2020). After the first screening of scientific data, 76 publications, including journal articles, conference papers, books, and online reports were found. Due to the lack of quantitative contributions, many documents ended up being omitted from the first search. As a final criterion, articles future simulations, projections with rele-

vant indicators and policies recommendations were selected. In addition, the search methodology uses key phrases such as "hydroelectric development in Ecuador"; "Hydropower projections in Ecuador"; and "Ecuadorian energy policies".

Throughout these documents, 28 selected papers are summarized, covering different application areas in the Ecuadorian hydropower development. Additional to know from direct sources data of the main hydropower projects in Ecuador, the following government agencies were consulted.

- Ministry of Energy and Non-Renewable Natural Resources of Ecuador (MERN, acronym named in Spanish)
- Electricity Corporation of Ecuador (CELEC, acronym named in Spanish)

The data were analyzed with scientific articles and information from government agencies that regulate energy development in Ecuador, generating indicators as annual energy consumption, per capita consumption ratio, and hydropower growth. On the one hand, for analyzing the energy projection of Ecuador, we took the base case of 2020, according to the historical record of the Ministry of Energy and Non-Renewable Resources, which grows at a percentage rate of 4.9%, and a quantitative percentage point that increased to the global trend of the hydropower expansion.

4 Results

To approach the topic, we divided the paper into two significant issues the Ecuadorian hydropower development of the recent years, and the country projections.

4.1 Ecuadorian hydropower development in recent years

Among 2007 and 2015, Ecuador invested USD 6 billion in eight hydroelectric plants, doubling their capacity (Vaca-Jiménez et al., 2020); one of them was Coca Codo Sinclair. Nowadays this project is the principal in Ecuador, with 1,500 MW capacity, which supplies 30% of the current energy in the country since 2017 (Álvarez-Chiriboga, 2020). To illustrate the hydropower development in Ecuador, Figure 2 shows the principal basins and projects.

As well, the IHA placed Ecuador third among the globally countries, adding new capacity in 2016 (International Hydropower Association, 2018b). Moreover, the Electricity Corporation of Ecuador reported in 2020 that 80% of all energy is through hydropower, as shown Figure 3 with the energy grid trend of the country since 2010 (CELEC, 2020).

Figure 3 shows that there was an increase of more than double in the hydropower production in the last ten years. For example, in 2010, Ecuador contributed to around 8,000 GWh, and 24,000 GWh was supplied by 2020, which represented an increase in the period of about 300%. In addition to this hydropower rise, thermoelectric production was reduced by more than triple production in 2010, 9,000 GWh versus 2020 with 2,000 GWh (CELEC, 2020; MERNNR, 2018).

Additionally, data from the annual statistics of the British Petroleum Company in a global comparison per capita energy consumption for the year 2019 establishes that worldwide around 20,884 kWh per capita is required. In contrast, 11,884 kWh per capita in Ecuador is necessary; perhaps about 67% represents hydropower with 7,904 kWh per capita, as indicated Figure 4 (BP p.l.c., 2020).

By way of comparison between renewable energies, the production since 1985 in Ecuador is detailed. According to Figure 5, a vast difference of the hydropower deployment is shown over time, verifying a slow and regular growth until the year 2000. The development began to increase, then in 2008, new projects were gradually incorporated, and finally, in 2017 there were around 20 TWh of hydropower production compared to 4 TWh in 1985 (MERNNR, 2018; Ritchie and Roser, 2020).

Figure 5 shows the hydropower in Ecuador supply increased from 4 TWh to 24 TWh in 35 years (1985 to 2020); it also indicates that other renewables such as wind and solar have reduced growth, with almost no relevance of contribution to the energy grid. Hence, in recent years, this representative hydropower development of Ecuador is pertinent to analyzing the effects and external parameters as the climate change. The country currently depends on many hydropower projects, and this source is sensitive to climatic variations (Zhong et al., 2019).

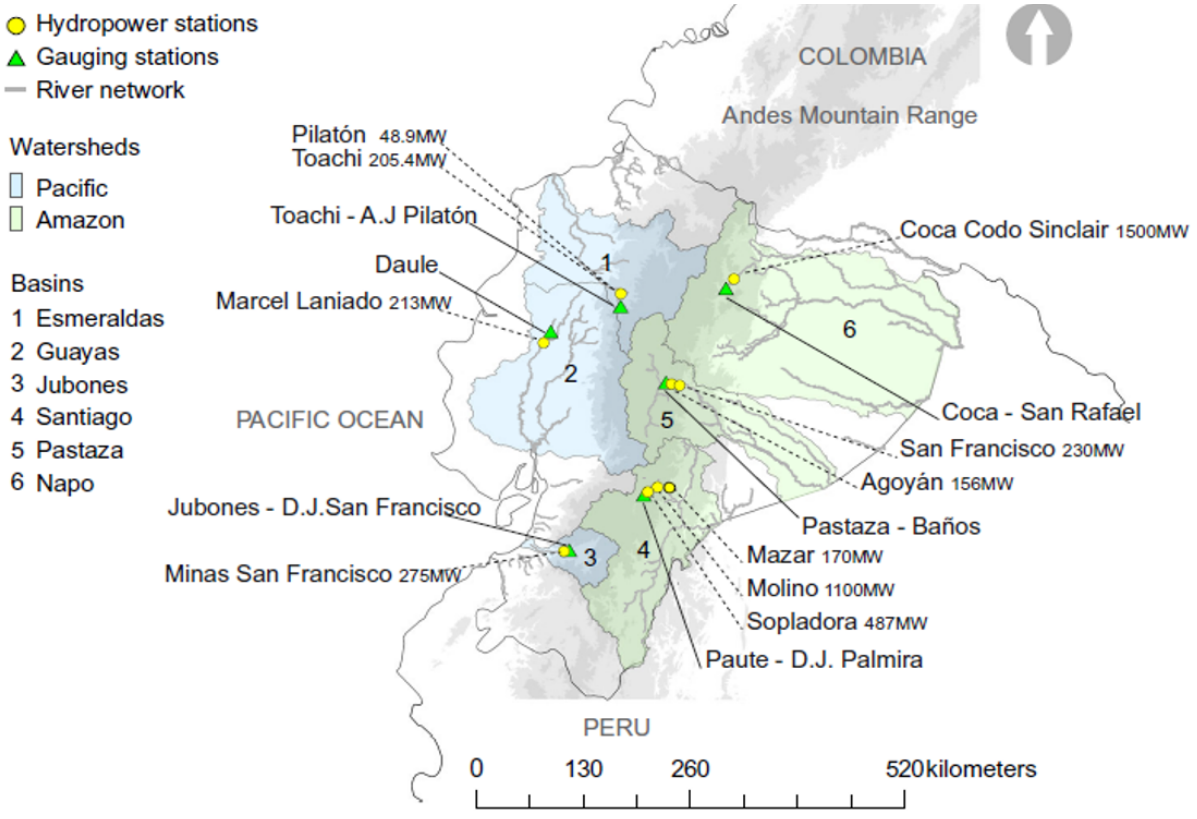

Figure 2. Main basins and hydropower projects in Ecuador.
Source: Carvajal et al. (2017).

According to the First Nationally Determined Contribution of Ecuador (NDC) of the Ministry of Environment and Water in 2019, an historical analysis of precipitation and average temperature for the 1960- 2015 period determined essential variations; the rains increased in the Coast 33%; Sierra 13%, and in the Amazon 1% of rainfall was reduced. In addition, there is an average temperature increase of 0,8° throughout (Ministerio de Medio Ambiente, Agua y Transición ecológica, 2019). Accordingly, the hydroelectricity depends on the availability of natural resources such as precipitation, which plays a fundamental role in the flow's runoff and the natural water cycle (Bakken et al., 2017; Van Vliet et al., 2016).

Additionally, it is necessary to mention that in Ecuador, being in the middle of the equatorial line, there are differences in precipitation between the north and south, where drought and hydropower sub-production are registered respectively due to its location, causing particularities to the time to analyze its trend and climate projection (Ponce-Jara et al., 2018).

Finally, before talking about the hydropower projections in Ecuador, it is important to mention that by 2021 there was 5,107 MW of hydropower installed, also according to the Regional Energy Integration Commission of South America, Ecuador has a feasible hydroelectric capacity of 23,120 MW, representing an installation of 22% so far of this renewable (Regional Energy Integration Commission of South America, 2021).

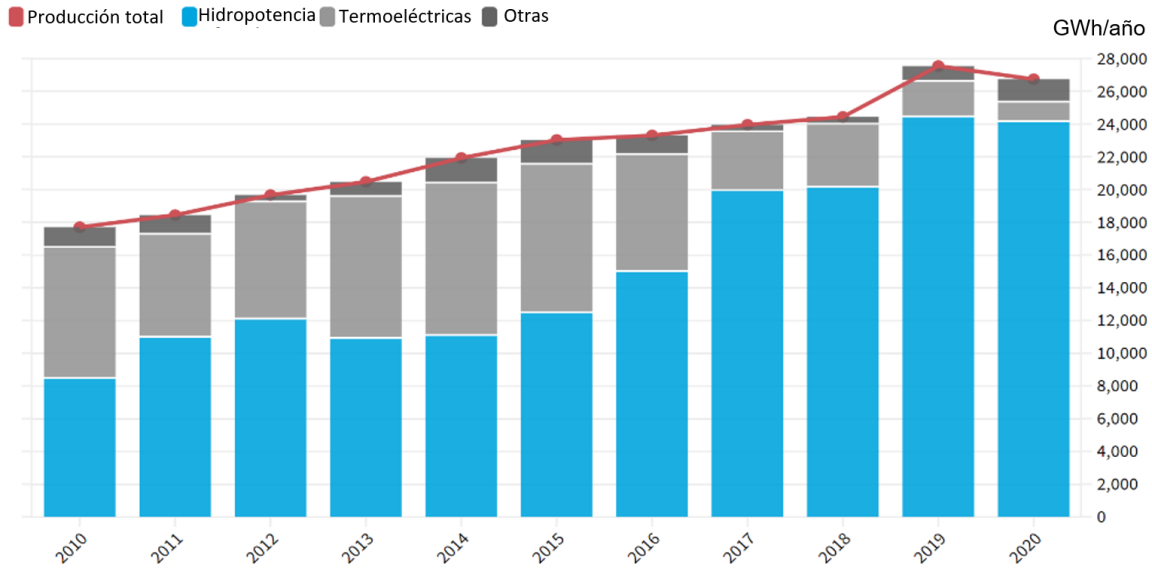

Figure 3. Ecuador energy production GWh / year.
Source: CELEC (2020).

4.2 Hydropower projections in Ecuador

According to the MERN of Ecuador in the Electricity Master Plan projected until 2027, 645 MW would be incorporated with 14 projects that will provide average annual energy of 3,491 GWh. Out of the 14 projects under construction, 11 correspond to hydropower projects with 407.5 MW, i.e., 63% of the planning, two thermoelectric projects with a capacity of 187 MW, and one wind power project with a power of 50 MW, as indicated in Table 2.

Table 2 shows that hydropower development will continue to be essential in Ecuador. In addition to the small and medium hydropower projects exposed, the data shows public and private investment at 88% and 12%, respectively. Nevertheless, two large hydropower projects seek to continue the hydro expansion strategy due to their capacity; these are Santiago and Cardenillo, as shown in Table 3.

However, this two hydropower have no interest due to the representative amounts of invest necessary and their degree of progress only in studies; they do not constitute plants with the certainty of execution to include them in the current energy expansion. However, with short-term projections, the MERN of Ecuador must define these projects as priorities and the State should put out tenders to attract international funds, which can be partly constituted by carbon credits, since they are renewable sources projects, which generally have 50 years of life.

Nevertheless, the projections, the population growth, and consumption constantly require additional electricity generation despite the current hydropower facilities; the Ministry of Energy and Non-Renewable Natural Resources data establishes the trend of growing historical annual energy consumption of Ecuador in 4.89%. Therefore, it is necessary to think in the short and medium term about continuing to implement renewable projects, not only hydroelectric.

Under this background, at the researcher discretion, three growth trends are projected until 2030 based on the real consumption of Ecuador in 2020 and taking the historical annual increase of 4.9% of the MERN. In addition, the researcher increased one percentage point for the following two trends, in the medium case 5.9%, and high scenario 6.9% as a conservative trend of energy needs for the country. As shown in Table 4, Ecuador will need in 2030 around 43 TWh, 47 TWh, or 52 TWh of energy, according to the scenarios proposed (low, medium, high) respectively, which will require a wide renewable and non-renewable development. As a reference, if more hydropower projects are implemented, they should use instruments such as the Hydro-

power Sustainability Assessment Protocol (HSAP) that contains concepts and suggestions for the countries that build these projects at a global level to manage sustainability criteria (International Hydropower Association, 2018a).

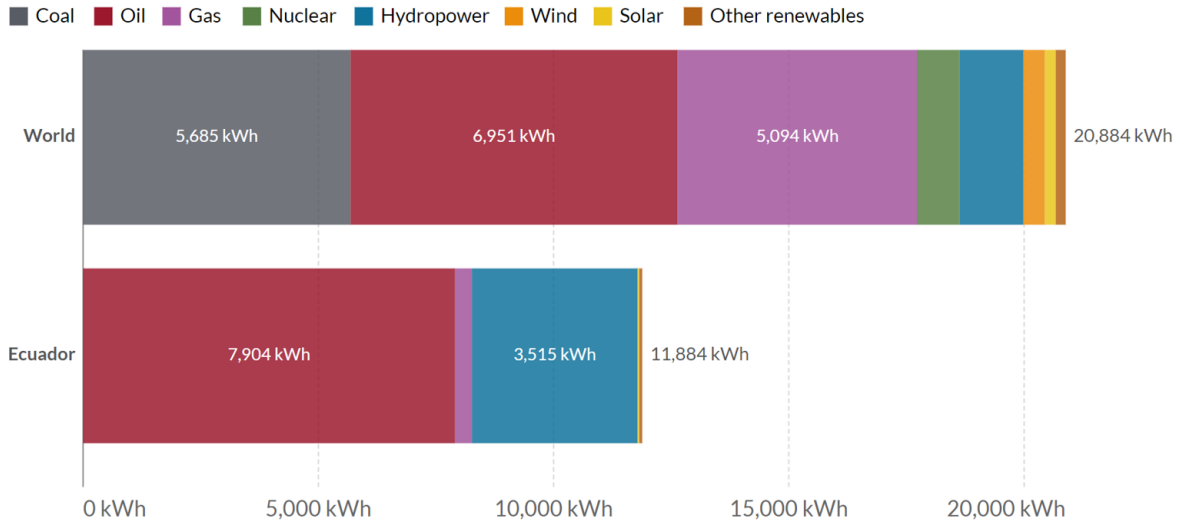

Figure 4. Consumption per capita primary energy by source 2019.
Source: (BP p.l.c., 2020).
Note: On the figure the term "oil" represents fossil fuels destined to produce thermoelectricity.

On the other hand, comparing the tendencies, according to an investigation of long-term role of hydroelectric systems towards compliance with the Nationally Determined Contribution of Ecuador, hydropower generates impacts by using environmental conditions, relating effects due to the water accumulation as water quality change, deforestation, and sub climate variations. Under this analysis Ecuador demonstrates uncertainty. The investigation shows that the energy provided by hydroelectricity would vary significantly between 53% to 81% by the year 2050, hence the Ecuadorian NDC goal would be deprived of the distribution of sizeable hydroelectricity structure. In addition, the study projections show that if there is a 25% decrease in hydropower availability, then accumulated CO_2 emissions by the use of fossil fuels will double (Carvajal et al., 2019; Guallpa et al., 2022). Also, for long term, the simulations determine that the impacts quantified for 2071-2100 has a wide range of annual difference; hydropower production in Ecuador varies between - 55% and + 39% of the historical average (Carvajal et al., 2017).

Furthermore, the Nationally Determined Contributions based on hydropower are highly vulnerable to the appearance of a dry climate scenario due to climatic variations in the Amazon area. Moreover, given the pattern of seasonal rains in Ecuador independent of the amount of hydropower installed, the NDC goal requires a diversified portfolio and not essentially from renewable sources (Carvajal et al., 2019). For Ecuador, a more robust energy grid in the long term should make emphasis on an adequate diversification of generation technologies with the sustenance of policies to rise non-conventional renewables (solar, wind, tidal, and geothermal) (Carvajal et al., 2017). The Inter-American Development Bank determines that in the future hydroelectricity is projected as a source of support, enabling other renewables (Alarcon, 2019).

Table 2. Energy projects in construction or planned in Ecuador.
Source: (Ministerio de Energía y Recursos No Renovables, 2019).

Project	Type of investment	Type	Capacity [MW]	Average power [GWh/year]	State
Toachi Pilaton	Public	Hydropower	254.4	1120	Santo Domingo
Machala Gas	Public	Thermoelectric	110	690	El Oro
Machala Gas Tercera	Public	Thermoelectric	77	510	El Oro
Minas de Huascachaca	Public	Wind	50	119	Loja
Quijos	Public	Hydropower	50	355	Napo
Piatua	Private	Hydropower	30	210.5	Pastaza
Sabanilla	Private	Hydropower	30	210.5	Zamora Chinchipe
Río Verde Chico	Private	Hydropower	10	74.3	Tungurahua
Chalpi Grande	Public	Hydropower	7.59	36	Napo
Mazar - Dunas	Public	Hydropower	7.38	41.4	Cañar
Mazar San Antonio	Public	Hydropower	7.19	44.9	Cañar
San José de Minas	Private	Hydropower	5.95	48	Pichincha
Chorrillos	Public	Hydropower	4	23.2	Zamora Chinchipe
Ulba	Private	Hydropower	1.02	8.4	Tungurahua
Total			**644.5**	**3 490.6**	**-**

Note: IRENA defines. Small projects $\leq$ 300 MW of capacity, medium to 11 MW $\leq$ 300 MW, and large up to 301 MW.

In addition, in an ecosystem assessment carried out in Ecuador, Briones-Hidrovo et al. (2020) in a study of five installed hydropower projects: Baba, Marcel Laniado, Alazán, Mazar - Dudas, and San Antonio determined that faced the climatic and ecological collapse the world has an objective to develop renewable energies. However, there are environmental problems due to the deep interaction with the immediate areas moving people from the original communities and lifestyle change (Briones-Hidrovo et al., 2020; Hasan and Wyseure, 2018).

Parra (2020) explains that hydropower in Ecuador is susceptible to climate variations. The studies exposed that hydroelectric capacity could display substantial sensitivities to differences in rainfall patterns. In Ecuador, this can change precipitation patterns, especially in high Tropical Andean regions. In the last years, the promotion of hydropower plants produced a reduction in fossil fuel burning. In spite of this, considering the possible impacts of climate change on this renewable, as occurred in 2009, the hydroelectric energy was affected by dry weather conditions (Cabrera et al., 2021; Parra, 2020).

Finally other study determines the capacity to 2030 of the five important hydroelectric projects of Ecuador (Coca Codo Sinclair, Manduriacu, Minas San Francisco, Toachi Pilaton, and Delsintagua). These plants were projected to have an initially capacity of 2 275 MW, however the investigation concludes that from the Intergovernmental Panel on Climate Change three scenarios (A1, B1, and B2) there are important capacity decreases, for example in the line called A1 there is a reduction of 1 839 MW to 2050, in B1 scenario is projected to 1 995 MW, and in the conservative scenario B2 up to 2 104 MW. Concluding in the A1, B1, and B2 scenarios, the capacity of these plants will decline by 19%, 12%, and 8%, respectively (Naranjo-Silva and Quimbita, 2022).

Summarizing the projections, the value of ecosystem services declined with the hydroelectric projects structure; renewable source exploitation implies degradation and suppression of ecological services. Therefore, it reduces the ecosystem's capacity to provide all its functions quantitatively and qualitatively, proposing a worrying issue, given that hydropower should not be sponsored as a sustainable energy source (Briones-Hidrovo et al., 2017, 2019). In addition, studies mention that hydropo-

wer depends on a strategic ubication and capacity but has some social, environmental and cultural issues as unbalances in the aquatic life before and after the reservoir, fragmentation and transformation of rivers, destroying ecosystems, reducing fishery resources and sometimes using territories from far communities, thus forcing those people to relocate (Voegeli et al., 2019; Zarfl et al., 2019).

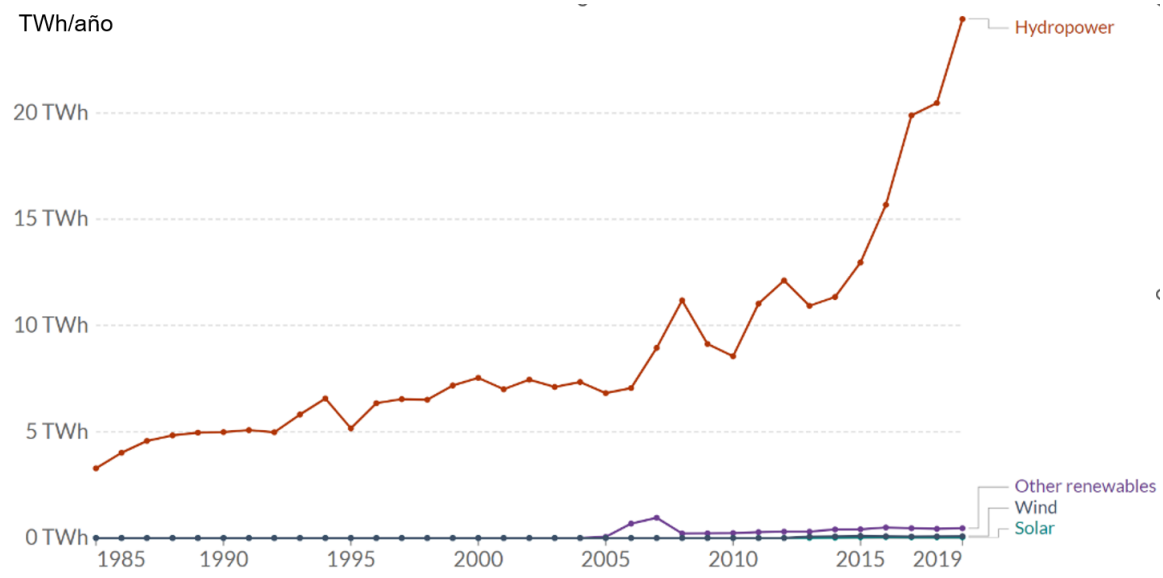

Figure 5. Renewable energy production by source in Ecuador in 2019.
Source: (Ritchie and Roser, 2020).

5 Discussion

In order to achieve global energy sustainability, renewable energy must replace fossil fuel burning (Camayo et al., 2021; García-Parra et al., 2022). However, at a global level, the hydropower production presents a broad vision of the advantages, and little is explained about the disadvantages and problems; hence, scientific studies show that hydropower generation has several implications, generating impacts on ecosystems due to the large infrastructure's development (Naranjo-Silva and J., 2021).

In Ecuador, large hydropower infrastructures have quickly developed for 15 years due to conditions with great availability of water, but to what extent is this water overuse sustainable? According to the IHA, Ecuador ranked third for globally nations that added new hydroelectricity projects last years (International Hydropower Association, 2018b).

On the other hand, global studies were carried out on climate impacts and aggressive hydropower development; for example, Lehner (2005) estimates that the gross hydropower potential will decrease by approximately 6 % to 12 % by Europe 2070s (Lehner et al., 2005). Estimates in vulnerable or modified regions establish that globally, a trillion dollars are cumulatively required to offset the deterioration of the last 18 years of hydropower generation associated with climate change (Turner et al., 2017).

According to Hofstra et al. (2019), climate change poses a global threat to hydropower and thermoelectric production. Through coupled hydrological modeling, options for sustainable adaptation of water and energy are evaluated. For the time scenario 2040-2069, the study estimates a reduction of 61 %-74 % in the usable capacity of hydropower and thermoelectric projects.

Table 3. Hydropower projects of more than 500 MW in Ecuador.

Project	Project phase	Capacity [MW]	Average power [GWh/year]	State	Specific location
Santiago	Feasibility and definitive design	2400	14 613	Morona Santiago	Twinza
Cardenillo	Feasibility and definitive design	596	3409	Morona Santiago	Méndez
Total		2996	18 022	-	-

An analysis in China indicates that hydropower is sensitive and vulnerable to climatic fluctuations, temperature and rain are the most important factors; therefore, extreme meteorological phenomena such as rain, heatwaves, floods, and drought, impose challenges for the hydroelectric development of the country with the highest global installed capacity with 356 GW (2020 year) (Fan et al., 2020).

Studies in India conclude that all hydrological basins experience substantial changes in precipitation and temperature that affect the water availability for hydropower production, and a warmer and more humid climate is observed in the future; therefore, it is calculated that the average annual temperature will increase between $18 \pm 14{,}6\%$ until the end of the century (Ali et al., 2018).

With the global comparations, the Ecuador results showed a rapid hydropower expansion last years. Nowadays is the principal energy source, and the middle conservative scenario by 2030 determines a 47 TWh needed to the country. Nevertheless, Escribano (2013) in an Ecuadorian energy policies analysis, mentions it is apparent that the hydroelectricity expansion faces regulatory, financial, and social problems, underlining the serious importance of undertaking an exhaustive examination of the energy grid relating to the country development versus the environmental conservation.

In addition, as mentioned in the section of hydropower projections in Ecuador, there is a 22% feasible installed capacity with data from 2021, but due to the differences in precipitation between the north and south of Ecuador, where drought and under-production are registered hydroelectric respectively, it is technically complicate to materialize additional projects that require robust analysis in addition to the constant climatic variations. Therefore, achieving the total feasible hydropower capacity would depend on resources, which means investment that the country does not have, because at the moment (December 2022 cutoff), the public debt is around 73,114 million dollars (Llerena-Montoya et al., 2021). In addition to the economic costs as an obstacle to new investments in hydroelectric systems, technical and administrative areas due to the lack of advance of final feasibility and engineering studies do not allow the specific development of this type of structures that finally also have environmental repercussions on virgin ecosystems that are in places far from the main cities.

In an energy scenarios study in Ecuador, Villamar2019, Villamar2021 show that the climate change influences would hinder the hydroelectric capacity to contribute to the fulfillment objectives as a country to lower the greenhouse gases that cause global warming. Although hydropower is presented in a renewable way, it shows environmental impacts, making a subsector of special consideration for its development (Chiang et al., 2013). Overall, the global trend is to develop more hydropower projects to mitigate the pollution of greenhouse gases from fossil generation sources. However, nowadays, in Ecuador, there are some impacts from this renewable source. It is essential to consider that growth and energy supply requires a specific analysis of the hydropower infrastructure. Substantial changes in precipitation and temperature are globally expected to affect water availability for hydroelectric generation making Ecuador a vulnerable country (Ali et al., 2015; Mousavi et al., 2018).

Table 4. Scenarios of energy demand in Ecuador Country.
Source: (Ministerio de Energía y Recursos No Renovables, 2019).

Year	Low [GWh]	Medium [GWh]	High [GWh]
2020 (Base)	26 727	26 727	26 727
2021	28 037	28 304	28 571
2022	29 410	29 974	30 543
2023	30 852	31 742	32 650
2024	32 363	33 615	34 903
2025	33 949	35 598	37 311
2026	35 613	37 699	39 886
2027	37 358	39 923	42 638
2028	39 188	42 278	45 580
2029	41 108	44 773	48 725
2030	43 123	47 414	52 087
Percentage of variation 2020-2027	4.90%	5.90%	6.90%

Finally, this manuscript has a general brief of hydropower in Ecuador with data analysis, however, it is still only an example of a small country in Latin America with a substantial water ability. In order to know in depth, the repercussions of hydroelectricity, especially in large scale, more information should be obtained from countries such as Brazil, China, and the United States, where hydroelectric expansion is greater in installed capacity.

6 Conclusions

Hydropower in Ecuador has overgrown in the last years; in 1985, the country generated 4 000 GWh; in 2010, Ecuador contributed around 8 000 GWh. By 2020, it supplied 24 000 GWh, which represented a relative increase for 2010- 2020, around + 300%.

Based on the Ministry of Environment and Water's estimate of temperature and precipitation changes, the projections performed by the energy grid and hydropower plants of Ecuador are subject to uncertainty. Moreover, by 2030, the country will require the low, medium, and high energy scenario at around 43 123 GWh, 47 414 GWh, and 52 087 GWh, respectively, and hydroelectricity will remain to be an essential renewable source for the country.

By the projections for Ecuador to 2030, a medium conservative average growth of 5.9% annual energy consumption was established as the principal scenario. But, regardless of the percentage of installed hydropower capacity, an expansion not necessarily renewable will be required for the future, which could cause a noticeable environmental imbalance.

Ecuador is a global example of managing an energy grid with more than 80% hydropower by 2020. Therefore, this renewable development relates the fragility finding to the ecosystems surrounding hydropower projects, generating a new issue plus climatic change effect.

Future research could analyze the strong interaction of hydropower to the installed ecosystems with availability modeling of water and environmental change. Also, it is recommended to develop and apply sustainability criteria through a methodology climate assessment, economic, environmental, and social to offset the effects produced by the hydropower projects.

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Author Contributions

SNS; Conceptualization, data processing, formal analysis, supervision, validation, research, writing, editing, writing the original draft and the final version of the manuscript.

References

Alarcon, A. (2019). The hydroelectric plants in latin america, where are we? and where are we going? Energuía para el futuro. Online: https://n9.cl/m5wq2.

Ali, S., Aadhar, S., Shah, H., and Mishra, V. (2018). Projected increase in hydropower production in india under climate change. *Scientific reports*, 8(1):12450. Online: https://n9.cl/pig3o.

Ali, S., Li, D., Congbin, F., and Khan, F. (2015). Twenty first century climatic and hydrological changes over upper indus basin of himalayan region of pakistan. *Environmental Research Letters*, 10(1):014007. Online: https://n9.cl/hrz5i.

Álvarez-Chiriboga, D. (2020). Modelo de predicción de la producción de energía de la central hidroeléctrica coca codo sinclair, basado en técnicas de aprendizaje computacional. Master's thesis, Universidad de las Fuerzas Armadas ESPE.

Bakken, T., Killingtveit, Å., and Alfredsen, K. (2017). The water footprint of hydropower production—state of the art and methodological challenges. *Global Challenges*, 1(5):1600018. Online: https://n9.cl/vgh0q.

BP p.l.c. (2020). Statistical review of world energy. 69th edition. online:https://bit.ly/48x0Uv0. Technical report, BP p.l.c.

Briones-Hidrovo, A., Uche, J., and Martínez, A. (2017). Accounting for ghg net reservoir emissions of hydropower in ecuador. *Renewable Energy*, 112:209–221. Online: https://n9.cl/6cnos.

Briones-Hidrovo, A., Uche, J., and Martínez, A. (2019). Estimating the hidden ecological costs of hydropower through an ecosystem services balance: A case study from ecuador. *Journal of cleaner production*, 233:33–42. Online: https://n9.cl/abt1u.

Briones-Hidrovo, A., Uche, J., and Martínez, A. (2020). Determining the net environmental performance of hydropower: A new methodological approach by combining life cycle and ecosystem services assessment. *Science of the Total Environment*, 712:136369. Online: https://n9.cl/o0pdt.

Cabrera, S., Eurie, M., Lock, K., Vandenbroucke, M., Oña, T., Gualoto, M., and Goethals, P. (2021). Variations in benthic macroinvertebrate communities and biological quality in the aguarico and coca river basins in the ecuadorian amazon. *Water*, 13(12):1692. Online: https://n9.cl/gkzqz.

Camayo, B., Quispe, M., Condezo, D., Massipe, J., Galarza, J., and Mucha, E. (2021). Autonomous solar thermal system design for indirect dehydration of aguaymanto (physalis peruviana l.), junín. *La Granja*, 33(1):114–123. Online: https://n9.cl/v6zka.

Carvajal, P., Anandarajah, G., Mulugetta, Y., and Dessens, O. (2017). Assessing uncertainty of climate change impacts on long-term hydropower generation using the cmip5 ensemble—the case of ecuador. *Climatic Change*, 144:611–624. Online: https://n9.cl/ow3ag.

Carvajal, P., Li, F., Soria, R., Cronin, J., Anandarajah, G., and Mulugetta, Y. (2019). Large hydropower, decarbonisation and climate change uncertainty: Modelling power sector pathways for ecuador. *Energy Strategy Reviews*, 23:86–99. Online: https://n9.cl/ul5pv.

CELEC (2020). Celec ep genera y transmite más del 90 por ciento de la energía eléctrica limpia que consume el país y exporta a los países vecinos. CELEC. Online: https://n9.cl/rz5slf.

Chiang, J., Yang, H., Chen, Y., and Lee, M. (2013). Potential impact of climate change on hydropower generation in southern taiwan. *Energy Procedia*, 40:34–37. Online: https://n9.cl/lc2yd.

CISPDR and SENAGUA (2016). *Plan nacional de la gestión integrada e integral de los recursos hídricos de las cuencas y microcuencas hidrográficas de Ecuador*. CISPDR.

Escribano, G. (2013). Ecuador's energy policy mix: Development versus conservation and nationalism with chinese loans. *Energy Policy*, 57:152–159. Online: https://n9.cl/yvgbtp.

Fan, J., Hu, J., Zhang, X., Kong, L., Li, F., and Mi, Z. (2020). Impacts of climate change on hydropower generation in china. *Mathematics and Computers in Simulation*, 167:4–18. Online: https://n9.cl/3hm24.

García-Parra, M., De la Barrera, F., Plazas-Leguizamón, N., Colmenares-Cruz, A., Cancimance, A., and Soler-Fonseca, D. (2022). Los objetivos de desarrollo sostenible en américa: Panorama. *La Granja: Revista de Ciencias de la Vida*, 36(2):46–59. Online:https://bit.ly/4aUrvUx.

Guallpa, M., Célleri, R., and Crespo, P. (2022). Efecto del coeficiente teórico de descarga de vertederos sobre la medición de caudales en pequeños ríos andinos. *La Granja: Revista de Ciencias de la Vida*, 36(2):75–87. Online:https://bit.ly/4b3NJn5.

Guilcatoma-Aimacaña, V. (2010). Inventario de las especies vegetales nativas del cerro teligote cantón pelileo, provincia del tungurahua desde los 3200 hasta los 3420 msnm. Master's thesis, Universidad Técnica de Ambato.

Hasan, M. and Wyseure, G. (2018). Impact of climate change on hydropower generation in rio jubones basin, ecuador. *Water Science and Engineering*, 11(2):157–166. Online: https://n9.cl/z7o9x.

Hidalgo, D., Ruíz, J., Maisincho, L., Cáaceres, B., Crespo Pérez, V., Domínguez, C., Piedra, D., and Villacís, M. (2024). Retroceso del glaciar del carihuairazo y sus implicaciones en la comunidad de cunucyacu. *La Granja: Revista de Ciencias de la Vida*, 39(1):[Acceso Temprano]. Online:http://doi.org/10.17163/lgr.n39.2024.06.

Hofstra, N., Kroeze, C., Flörke, M., and van Vliet, M. (2019). Editorial overview: Water quality: A new challenge for global scale model development and application. *Current opinion in environmental sustainability*, 36:A1–A5. Online: https://n9.cl/37pxz.

ICOLD (2019). General synthesis of world register of dams. ICOLD. Online: https://n9.cl/l6t65.

International Hydropower Association (2018a). Hydropower sustainability assessment protocol (vol. 56, issue 3). Technical Report. Online: https://doi.org/10.1111/fcre.12351.

International Hydropower Association (2018b). Hydropower sustainability guidelines on good international industry practice. International Hydropower Association. Online:https://bit.ly/424O30D.

International Hydropower Association (2021). Hydropower status report 2021: Sector trends and insights. International Hydropower Association. Online:https://www.hydropower.org/publications/2021-hydropower-status-report.

International Renewable Energy Agency (2020). Renewable Energy Capacity Highlights 2019. Irena, 00(March 2020), 1–3. International Renewable Energy Agency. Online: https://www.irena.org/publications.

IRENA (2020). *Renewable Energy Statistics 2020*, chapter Renewable hydropower (including mixed plants), pages 16–21. International Renewable Energy Agency.

IRENA (2021). *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency.

Jin, Y., Andersson, H., and Zhang, S. (2016). Air pollution control policies in china: a retrospective and prospects. *International journal of environmental research and public health*, 13(12):1219. Online: https://n9.cl/b4fh9.

Killingtveit, Å. (2018). *Managing Global Warming: An Interface of Technology and Human Issues*, chapter Hydropower, pages 265–315. International Renewable Energy Agency.

Lehner, B., Czisch, G., and Vassolo, S. (2005). The impact of global change on the hydropower potential of europe: a model-based analysis. *Energy Policy*, 33(7):839–855. Online: https://n9.cl/q63q3.

Llamosas, C. and Sovacool, B. (2021). The future of hydropower? a systematic review of the drivers, benefits and governance dynamics of transboundary dams. *Renewable and Sustainable Energy Reviews*, 137(0327):110–124. Online: https://doi.org/10.1016/j.rser.2020.110495.

Llerena-Montoya, S., Velastegui, A., Zhirzhan, B., Herrera, V., Adami, M., de Lima, A., Moscoso, F., and Encalada, L. (2021). Multitemporal analysis of land use and land cover within an oil block

in the ecuadorian amazon. *ISPRS International Journal of Geo-Information*, 10(3):191. Online: https://n9.cl/arbzn.

Lu, S., Dai, W., Tang, Y., and Guo, M. (2020). A review of the impact of hydropower reservoirs on global climate change. *Science of the Total Environment*, 711:134996. Online: https://n9.cl/bs7su.

Mena-Vasconez, P. (2018). Biodiversity ecuador. p. 16.

MERNNR (2018). National energy efficiency plan. 2018. online:https://bit.ly/48yZj7Q. Technical report, BP p.l.c.

Ministerio de Energía y Recursos No Renovables (2019). Plan maestro de electricidad. Ministerio de Energía y Recursos No Renovables. Online:https://n9.cl/ayhst.

Ministerio de Medio Ambiente, Agua y Transición ecológica (2019). First contribution determined at the national level to the paris agreement under the united nations framework convention on climate change. Ministerio de Medio Ambiente, Agua y Transición ecológica. Paper Knowledge. Toward a Media History of Documents. Online:https://bit.ly/48OLlyu.

Mousavi, R. S., Ahmadizadeh, M., and Marofi, S. (2018). A multi-gcm assessment of the climate change impact on the hydrology and hydropower potential of a semi-arid basin (a case study of the dez dam basin, iran). *Water*, 10(10):1458.

Naranjo Silva, S. and Álvarez, J. (2021). An approach of the hydropower: Advantages and impacts. a review. *Journal of Energy Research and Reviews*, 8(1):10–20. Online: https://n9.cl/dfnky.

Naranjo-Silva, S. and J., Á. (2021). Hydropower: Projections in a changing climate and impacts by thisçlean"source. *CienciAmérica*, 10(2):32–45. Online: https://n9.cl/arwut.

Naranjo Silva, S., Punina, D., and Morales, J. (2021). Energía solar en paradas de bus una aplicación moderna y vanguardista. *Revista InGenio*, 4(1):58–68. Online: https://n9.cl/0t8k5.

Naranjo-Silva, S. and Quimbita, O. (2022). Hydropower and climate change concerning to the implementation of the first national determined contribution in ecuador. *Revista Iberoamericana Ambiente & Sustentabilidad*, (5):268. Online: https://n9.cl/9e0a3.

Parra, R. (2020). Contribution of non-renewable sources for limiting the electrical co2 emission factor in ecuador. *WIT Trans. Ecol. Environ*, 244:65–77. Online: https://n9.cl/xohgi.

Ponce-Jara, M., Castro, M., Pelaez, M., Espinoza, J., and Ruiz, E. (2018). Electricity sector in ecuador: An overview of the 2007–2017 decade. *Energy Policy*, 113:513–522. Online: https://n9.cl/5nmoyw.

Purcell, T. and Martínez, E. (2018). Post-neoliberal energy modernity and the political economy of the landlord state in ecuador. *Energy Research & Social Science*, 41:12–21. Online: https://n9.cl/pw5afo.

Regional Energy Integration Commission of South America (2021). Energy publications of south america. Technical Reports. Online: https://www.cier.org/es-uy/Paginas/Publicaciones.aspx.

Ritchie, H. and Roser, M. (2020). Renewable energy - our world in data. Our World in Data. Online: https://n9.cl/9zvwk.

Schaefli, B. (2015). Projecting hydropower production under future climates: a guide for decision-makers and modelers to interpret and design climate change impact assessments. *Wiley Interdisciplinary Reviews: Water*, 2(4):271–289. Online: https://n9.cl/dl2oi.

Teräväinen, T. (2019). Negotiating water and technology—competing expectations and confronting knowledges in the case of the coca codo sinclair in ecuador. *Water*, 11(3):411. Online: https://n9.cl/gmdeg.

Turner, S.and Hejazi, M., Kim, S.and Clarke, L., and Edmonds, J. (2017). Climate impacts on hydropower and consequences for global electricity supply investment needs. *Energy*, 141:2081–2090. Online: https://n9.cl/hvuq4.

Vaca-Jiménez, S., Gerbens, P., and Nonhebel, S. (2020). The monthly dynamics of blue water footprints and electricity generation of four types of hydropower plants in ecuador. *Science of The Total Environment*, 713:136579. Online: https://n9.cl/cu5bj.

Van Vliet, M., Wiberg, D., Leduc, S., and Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, 6(4):375–380. Online: https://n9.cl/4387x.

Voegeli, G., Hediger, W., and Romerio, F. (2019). Sustainability assessment of hydropower: Using causal diagram to seize the importance of impact pathways. *Environmental Impact Assessment Review*, 77:69–84. Online: https://n9.cl/bk2hd.

Zarfl, C., Berlekamp, J., He, F., Jähnig, S., Darwall, W., and Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. *Scientific reports*, 9(1):18531. Online: https://n9.cl/aml8v.

Zhong, R., Zhao, T., He, Y., and Chen, X. (2019). Hydropower change of the water tower of asia in 21st century: A case of the lancang river hydropower base, upper mekong. *Energy*, 179:685–696. Online: https://n9.cl/400jc.

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Sustainable Development

Environmental Regulations in Eco-innovation and Sustainable Performance in Mexican Automotive Industry

Efectos de las Regulaciones Medioambientales en la Eco-innovación y el Rendimiento Sustentable en la Industria Automotriz Mexicana

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Abstract

In the literature, evidence has been provided that establishes that compliance with environmental regulations promotes the adoption and implementation of eco-innovation activities in manufacturing firms, since through this type of activities not only are the costs associated with the discharges of pollutants, but also increases the level of sustainable performance of companies. However, little is known about the relationship between environmental regulations, eco-innovation, and sustainable performance, since there are few studies published in the literature that have focused on their analysis, so this study aims to fill this existing gap, and generate new knowledge of the relationship between these three constructs through an extensive review of the literature. Likewise, a questionnaire was distributed to a sample of 460 manufacturing firms in Mexico, analyzing the data through confirmatory factor analysis and structural equation models based on covariance. The results obtained suggest that environmental regulations have positive effects on eco-innovation, and eco-innovation has positive effects on sustainable performance of manufacturing firms in the automotive industry. In this context, the results obtained allowed us to conclude that compliance with environmental regulations established by the public administration, by manufacturing firms in the automotive industry, improve both eco-innovation activities and sustainable performance of organizations.

Keywords: Environmental, regulation, environmental regulation, innovation, sustainable performance, eco-innovation, manufacturing firms, automotive industry.

Resumen

En la literatura se ha aportado evidencia que establece que el cumplimiento de las regulaciones medioambientales propicia la adopción e implementación de actividades de eco-innovación en las empresas manufactureras, ya que a través de este tipo de actividades no sólo se reducen los costos asociados a las descargas de contaminantes, sino también se incrementa el nivel del rendimiento sustentable de las empresas. Sin embargo, poco se sabe de la relación existente entre las regulaciones medioambientales, la eco-innovación y el rendimiento sustentable, ya que son pocos los estudios publicados en la literatura que se han orientado en su análisis, por lo cual este estudio tiene como objetivo llenar este vacío existente, y generar nuevo conocimiento de la relación entre estos tres constructos a través de una extensa revisión de la literatura. Asimismo, se distribuyó un cuestionario a una muestra de 460 empresas manufactureras de México, analizando los datos mediante el análisis factorial confirmatorio y los modelos de ecuaciones estructurales basados en la covarianza. Los resultados obtenidos sugieren que las regulaciones medioambientales tienen efectos positivos en la eco-innovación, y la eco-innovación tiene efectos positivos en el rendimiento sustentable de las empresas manufactureras de la industria automotriz. Bajo este contexto, los resultados obtenidos permitieron concluir que el cumplimiento de las regulaciones medioambientales establecidas por la administración pública, por parte de las empresas manufactureras de la industria automotriz, mejoran tanto las actividades de eco-innovación como el rendimiento sustentable de las organizaciones.

Palabras clave: Medioambiente, regulación, regulación medioambiental, innovación, eco-innovación, rendimiento sustentable, empresas manufactureras, industria automotriz.

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1 Introduction

In the last decade, environmental problems have become a topic of global interest and public debate in the literature (Geng and He, 2021), particularly because the development of society does not have to depend on natural resources depletion (Almeida and Wasim, 2023). In this regards, Emina (2021) considered that the economic development of countries should not only be subject to meeting the needs of the present, but also to guaranteeing the needs of future generations. Guo et al. (2020) supports this point of view, recommending the adoption of a combination of environmental and innovation policies, which allow long-term economic and business growth. Eco-innovation (EI) is emerging in the literature as one of the alternatives that firms have to improve and mitigate the negative effects that they generate on the environment (Cai and Li, 2018), and can help firms to improve sustainable performance (SP) (García-Parra et al., 2022; Almeida and Wasim, 2023).

Additionally, various studies published in the literature have suggested that EI can be considered as an alternative solution to global environmental problems (e.g. Afshari et al. (2020); García-Granero et al. (2020); Han and Chen (2021); Arranz et al. (2021)), particularly because when manufacturing firms adopt environmentally friendly innovations, the negative impacts of environmental pollution are reduced (García-Granero et al., 2020; Arranz et al., 2021). Likewise, Bitencourt et al. (2020) suggested that companies that prioritize environmental care in their policies can obtain greater long-term economic growth, which is why they should pay more attention to environmental and sustainability aspects (Muhammad et al., 2020).

In this context, EI is one of the most effective business strategies to protect the environment and SP (Porter and van der Linde, 1995), and plays a fundamental role in the economic growth of firms and countries (Yang and Yang, 2015). Therefore, there are more government authorities that are generating a series of environmental regulations (ER) to promote environmental firms to adopt EI (Yuan et al., 2017; Yuan and Xiang, 2018). However, the results obtained from studies that relate ER, EI and SP can be considered as inconclusive and open to debate (Dewick et al., 2019), which is why this study contributes to EI literature with the generation of new knowledge, in addition to that it also complements other work published in the literature (You et al., 2019). Therefore, to complement and expand the limited body of knowledge, this paper addresses the following research question: What is the relationship between ER, EI and SP in the automotive industry?

2 Materials and Methods

2.1 Environmental Regulations and Eco-innovation

To reduce negative impacts on the environment and promote sustainable economic development among manufacturing firms, public administration is increasingly intervening through ER, in stimulating companies to adopt measures that improve the environment and sustainability (Xie et al., 2023), especially because ER is one of the better environmental policy instruments (Wang and Zhang, 2022). Furthermore, ER can also stimulate companies to adopt EI, particularly highly polluting manufacturing firms, such as the automotive industry, in emerging economy countries, where the intensity of ER is generally very low (Wang, 2023), and the implementation of ER is required to improve EI capabilities of organizations (Xu et al., 2020).

The relationship between ER and EI has been recently explored in the literature in various studies (e.g. Liao and Tsai (2019); Wang et al. (2020); Frigon et al. (2020); Han and Chen (2021)), particularly from the implication of public administration in restricting regulations imposed on companies and organizations to safeguard ecosystems (Sanni, 2018). Along these lines, Frigon et al. (2020) considered that public administration should tighten environmental policies that would force manufacturing firms to adopt EI to generate pollution-free industries. In a recently published study, Han and Chen (2021) found that ER policies implemented by public administration in Myanmar, had a significant positive impact on the EI of manufacturing companies.

Also, public administration is generating increasingly stringent ER, and is pushing hard for manufacturing firms to comply with the four essential REs: (1) regulation of emissions of pollutants into

the environment, (2) tax for discharge of pollutants, (3) use of renewable energy and, (4) investments by plants in new local environmental improvement projects (Xie et al., 2017). In addition, public administration is promoting the adoption and implementation of the different activities involved in EI in all companies in the manufacturing industry, with the purpose of significantly reducing both energy and resource consumption and pollution levels and CO_2 generation (Guo et al., 2017; Liao, 2018). In this line, EI is considered today not only as one of the best strategies that helps manufacturing firms to comply with ER, but also in generating a higher SP (Shu et al., 2016; Wakeford et al., 2017).

Additionally, EI induced by strict compliance with ER is not only limited to innovation or technological advancement of manufacturing firms, but must also include optimization process, product design and production and the implementation of new methods of product management and distribution (Porter and van der Linde, 1995). However, most of the studies published in the literature have focused on the effects that ER have on technological innovation of manufacturing firms (Hojnik and Ruzzier, 2016; Costa-Campi et al., 2017; Wakeford et al., 2017), and relatively few studies have oriented in ER on EI of manufacturing firms (You et al., 2019). ER can promote the EI adoption among manufacturing firms, through the application of three elementary measures: prevention of environmental pollution, management of eco-products and sustainable development (You et al., 2019).

Under this context, ER plays an essential role in stimulating and promoting manufacturing firms, including those that make up automotive industry, to intensify actions in the reuse and recycling of materials in the production of more environmentally friendly products, through EI adoption (Han and Chen, 2021), since this would allow not only to reduce negative impacts on environment, but also to improve its level of competitiveness (Wang et al., 2020). Furthermore, ER imposed on manufacturing firms to protect the environment can generate a substantial increase not only in the demand for eco-products, but also stimulate the development of innovative techniques to improve environmental performance (Fernández et al., 2021). Thus, considering the information presented above, it is possible to propose the following research hypothesis:

H1: Environmental regulations have significant positive effects on eco-innovation.

2.2 Eco-innovation and Sustainable Performance

The innovation literature established that internal factors such as resources available in firms, structure and essential capacities determine in a high percentage EI implementation, while external pressure exerted by consumers, customers, environmental groups and public administration induces manufacturing firms to be more practical in adopting environmental practices (Cai and Li, 2018). In addition, recent studies have established that EI has significant positive effects on SP of manufacturing firms (e.g. Maldonado-Guzmán and Garza (2020); Almeida and Wasim (2023); Michalski et al. (2023)), since EI is considered as a strategy business that adds value to customers and companies, that contributes to improving both SP and reducing costs and environmental impacts (Tseng et al., 2021).

Likewise, EI can replace existing products in manufacturing firms with eco-products that are more environmentally friendly, which generally reduce negative impacts to the environment (Cai and Li, 2018), and can improve efficiency of resources and raw materials, reduce waste of materials and significantly reduce the costs associated with the generation of pollutants and CO_2 for not complying with ER (Cai and Li, 2018). In addition, EI products can generate additional profits or benefits that will allow manufacturing firms to obtain economic and financial resources necessary to develop EI activities, and establish a corporate image of environmental care responsibility, implement a diversification of its eco-products and increase its market share (Cai and Li, 2018). Also, manufacturing firms that have adopted EI commonly have higher productivity per employee, and economic and SP than those companies that have not yet done so (Hojnik and Ruzzier, 2016).

Additionally, various studies published in the literature have identified different determining factors in EI adoption and application, such as regulation (Han and Chen, 2021; Wasiq et al., 2023), government support (Wang et al., 2020), managerial pressure (Long et al., 2020; Wang et al., 2020), market pressure (Chen and Liu, 2019; Wasiq et al.,

2023), technological factors (Andersson et al., 2020; Wasiq et al., 2023), and business performance (Yurdakul and Kazan, 2020; Geng et al., 2021). However, there are relatively few studies published in the literature that have explored the influence of EI on SP (Maldonado-Guzmán and Garza, 2020; Almeida and Wasim, 2023). According to Wang et al. (2020), and Wasiq et al. (2023) government support is essential to encourage competition and promotion of innovative technologies.

In recent years, the analysis and discussion of EI adoption has gained significant attention from academics and researchers (e.g. Mercado-Caruso et al. (2020); Zhang et al. (2020); Fernández et al. (2021); Geng et al. (2021); Wasiq et al. (2023); Almeida and Wasim (2023)). One of the key factors in EI adoption and implementation in manufacturing firms, including the automotive industry, is the growing interest that consumers have in purchasing environmentally friendly products, which is closely linked to the commitment and desire to express identity through the purchase of green products (Fernández et al., 2021; Rana and Solaiman, 2022; Kautish and Khare, 2022), which encourages manufacturing firms to apply EI practices to improve their products, processes and management systems sustainability (Afshari et al., 2020; Chang et al., 2021).

Under this context, EI is generally categorized in the literature as an environmentally related innovation (Wang et al., 2020; Chang et al., 2021), particularly because EI has been shown to generate a positive impact on environmental levels of manufacturing firms, such as profitability (Kraus et al., 2020; Achmad et al., 2023), social performance (Wang et al., 2020), and SP (Singh et al., 2020; Al-Hanakta et al., 2023). Furthermore, recent studies published in the literature (e.g. Han and Chen (2021); Almeida and Wasim (2023)), suggest that ER can encourage manufacturing firms to adopt EI activities, which can generate greater SP level. Thus, considering the information presented above, it is possible to propose the following research hypothesis:

H2: Eco-innovation has significant positive effects on sustainable performance.

To respond to the two established research hypotheses, an empirical study was carried out in manufacturing firms of the Mexican automotive industry, particularly analyzing the relationship between ER, EI and SP. In the first phase of the study, a "Business Panel" was held with three academics from the innovation area and five businessmen from the automotive industry and two representatives of government agencies related to ER.

The results obtained in this first phase allowed the design of a questionnaire to collect the information, applying a pilot test to ten businessmen of the automotive industry, making minor adjustments in writing, appearance and spelling. Pilot studies are essential to ensure validity when questionnaires are self-administered or contain self-developed scales (Bryman, 2016; Hair et al., 2016).

2.3 Sample Design and Data Collection

The frame of reference used in this study was the directory of the companies of the Mexican automotive industry, which had registered 909 firms as of November 30, 2019, the companies belonging to various local, regional, and national business chambers, Therefore, the empirical study did not focus on a particular group or business association. In addition, the survey for the collection of information was applied to a sample of 460 companies selected by simple random sampling, with a maximum error of $\pm$ 4% and a level of reliability of 95% and applying the survey during the months of January to March 2020. Also, the questionnaire was delivered to the company manager who designated the people responsible for each area to answer the questions that corresponded to them, obtaining information from the experts in each organization area.

2.3.1 Measure Development

ER measurement is an adaptation to the scale established by Xie et al. (2017) and Pan et al. (2017), who considered that ER can be measured through 4 items. EI measurement was made to the scales proposed by Hojnik et al. (2014) and Segarra-Oña et al. (2014), being measured EI product through 4 items, EI processes through 4 items and EI management through 6 items.

Finally, SP measurement is an adaptation to the scale proposed by Gadenne et al. (2012), who measured this construct through 5 items. A five-point

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Likert-type scale was chosen to strike a balance between complexity for respondents and accuracy for analysis (Forza, 2016; Hair et al., 2016). Table 1 shows the items of the five scales used in paper.

Table 1. Measurement Model Assessment

Indicators	Constructs
Environmental Regulation (ER)	
ENR1	Regulation of emissions of pollutants into the environment
ENR2	Pollutant discharge tax
ENR3	Use of renewable energies
ENR4	Plant investments in new local environmental improvement projects
Product Eco-innovation (PE)	
PEI1	It constantly improves its product life cycle standards and conducts product life cycle studies
PEI2	It uses or develops new energy sources with a tendency to reduce CO_2 emissions
PEI3	It uses the eco-label system required by each destination country for its products
PEI4	It uses and elaborates eco-innovative components and materials that are made from recycled raw materials
Process Eco-innovation (RE)	
PRE1	Treats wastewater
PRE2	It uses sterilization methods for its components or technological devices
PRE3	Produces or uses fabric components that use fabric sanitization technologies
PRE4	It uses ecological or recyclable paper in its processes
Management Eco-innovation (ME)	
MEI1	Has a management system that reuses obsolete components and equipment
MEI2	Has an ISO 14001 Certification or similar
MEI3	It has constant audits of energy saving and ecology by the state and/or municipal authorities of its location
MEI4	Constantly conducts seminars or training courses for staff related to eco-innovatio
MEI5	It has well-defined policies that encourage and support eco-innovation activities throughout the organization
MEI6	It has a monitoring and control system for wastewated generated by the company
Sustainable Performance (SP)	
SPE1	It has among its objectives the care of the environment
SPE2	Makes great efforts to promote environmental care
SPE3	It has a great commitment to invest in projects that protect the environment
SPE4	Frequently discusses the results of environmental care performance within the organization.
SPE5	It has an excellent performance in protecting the environment compared to other companies in the same industry or sector.

Given that the data were collected by applying a questionnaire to the same informant (company manager), there is the possibility of causing biases that could generate Type I (false positive) or Type II (false negative) errors considered in this study, variance evaluation through the common method (CMV),

following Podsakoff et al. (2012) recommendations. Traditionally, the method most used by scientific and academic community to verify the possible effect of CMV is *Harman's one-factor test* (Podsakoff et al., 2003), which indicates that all items on the measured followed an exploratory factor analysis (EFA), forcing extraction to a single factor (Iverson and Maguire, 2000; Aulakh and Gencturk, 2000).

To verify the suitability of the data and the possible effect of CMV, an EFA was applied using principal components method and varimax rotation, finding a KMO value = 0.85 and a statistically significant Bartlett test ($X^2_{(1,035)}$ = 6.567,05; p < 0,000). If there was any inconvenience in the data or in the CMV, the common factor extracted should have a value greater than 50% of the variance extracted (Podsakoff et al., 2003), but the common factor extracted from the application of the EFA is 34.7%, which is much lower than the recommended value, which indicates the non-existence of CMV, which does not seem to have any effect on the relationships proposed between the variables (Podsakoff et al., 2012).

2.3.2 Reliability and Validity of Measurement Scales

The evaluation of reliability and validity of the three measurement scales required a Confirmatory Factor Analysis (CFA), using the maximum likelihood method with the support of the EQS 6.2 software (Bentler, 2005; Brown, 2006; Byrne, 2006). Therefore, for the measurement of reliability, Cronbach's Alpha and Composite Reliability Index (CRI) (Bagozzi and Yi, 1988) were used, and according to the results obtained in CFA all the values of the three scales are higher than 0.7 for both indices, which provides evidence of the reliability of the scales and justifies their internal reliability (Nunally, 1994; Hair et al., 2014). In addition, as evidence of convergent validity, CFA results indicate that all items of related factors are significant (p <0.001), and the size of all standardized factor loads is greater than 0.60 (Bagozzi and Yi, 1988).

The results of CFA application are presented in Table 2 and suggest that the measurement model provides a good statistical data fit (SBX^2 = 776.804; df = 2202; p = 0.000; NFI = 0.888; NNFI = 0.904; CFI = 0.916; RMSEA = 0.074). In addition, Table 2 shows a high internal consistency of the constructs, in each case *Cronbach's Alpha* exceeds the value of 0.70 recommended by Nunally (1994). CRI represents the variance extracted between the group of observed variables and the fundamental construct (Fornell and Larcker, 1981), so that a CRI greater than 0.60 is considered desirable (Bagozzi and Yi, 1988), in this study this value is widely surpassed. Extracted Variance Index (EVI) was calculated for each of the constructs, resulting in an EVI greater than 0.50 (Fornell and Larcker, 1981), in this work 0.50 is exceeded in all factors.

In addition, the discriminant validity of the theoretical model of ER, EI and SP were measured by means of two tests, which are presented in Table 3. First, confidence interval test is presented. (Anderson and Gerbing, 1988), which states that with a 95% confidence interval, none of the individual elements of the latent factors of the correlation matrix has the value of 1. Second, *variance extracted test* (Fornell and Larcker, 1981), which states that the variance extracted from each pair of constructs is lower than its corresponding EVI. Therefore, according to the results obtained from the application of both tests, it is possible to conclude that both tests demonstrate sufficient evidence of the existence of discriminant validity.

3 Results and Discussion

To respond to the two hypotheses raised in this empirical study, a structural equation model (SEM) was applied with the support of the EQS 6.2 software (Bentler, 2005; Byrne, 2006; Brown, 2006), analyzing the nomological validity of the theoretical model of ER, EI and SP through the Chi-square test, by means of which the results obtained between the theoretical model and the measurement model were compared, obtaining non-significant results which allows establishing an explanation of the observed relationships between latent constructs (Anderson and Gerbing, 1988). Table 4 shows the results obtained from the application of the SEM.

Table 4 shows the results obtained from the application of SEM and, with respect to the $\mathbf{H}_1$ hypothesis, the results obtained, β = 0.989 p <0.001, indicate that ER has significant positive effects on EI of manufacturing firms. Regarding the $\mathbf{H}_2$ hypothesis, the results obtained, β = 0.265 p <0.001, indicate

that EI has significant positive effects on SP of manufacturing firms. In summary, the existence of a significant positive relationship between ER, EI and SP can be corroborated.

Table 2. Internal consistency and convergent validity of the theoretical model

Variable	Indicator	Factorial Loading	Robust t-Value	Cronbach's Alpha	CRI	EVI
Environmental Regulations	ENR1	0.719***	1 000 [a]	0.913	0.914	0.728
	ENR2	0.852***	18.058			
	ENR3	0.954***	19.953			
	ENR4	0.871***	18.483			
Product Eco-innovation **(F1)**	PEI1	0.668***	1 000 [a]	0.874	0.875	0.639
	PEI2	0.801***	14.877			
	PEI3	0.893***	16.025			
	PEI4	0.819***	15.137			
Process Eco-innovation **(F2)**	PRE1	0.859***	1 000 [a]	0.916	0.917	0.736
	PRE2	0.884***	24.806			
	PRE3	0.877***	24.505			
	PRE4	0.809***	21.391			
Management Eco-innovation **(F3)**	MEI1	0.776***	1 000 [a]	0.926	0.927	0.681
	MEI2	0.758***	17.421			
	MEI3	0.862***	20.463			
	MEI4	0.889***	21.279			
	MEI5	0.886***	21.197			
	MEI6	0.769***	17.730			
Eco-innovation	**F1**	0.815***	5.806	0.821	0.822	0.609
	F2	0.686***	5.169			
	F3	0.831***	6.133			
Sustainable Performance	SPE1	0.751***	1 000 [a]	0.898	0.899	0.642
	SPE2	0.755***	16.237			
	SPE3	0.850***	18.450			
	SPE4	0.858***	18.634			
	SPE5	0.786***	16.959			

S-BX^2 (df = 220) = 776.804; $p < 0.000$; NFI = 0.888; NNFI = 0.904; CFI = 0.916; RMSEA = 0.074
[a] = Constrained parameters to such value in the identification process
*** = $p < 0.01$

The results selected in this empirical study have different implications for both managers and manufacturing firms. A first implication originated from these results is that the data derived from the application of 460 surveys confirmed the realization of a general analysis of the relationship between ER, EI (means through eco-innovation in products, processes, and management), and SP in a particular industry (Mexican automotive industry), so in future studies these three constructs in longitudinal studies or in case studies of success will be relevant. However, from the point of view of the evolution of innovation, the results indicate that full compliance with ER improves EI activities of manufacturing firms (You et al., 2019; Dewick et al., 2019).

A second implication derived from the results is that ER allow manufacturing firms, not only to implement eco-investment and eco-planning activities in EI of products, processes and management, as suggested previously in published studies (e.g., Wakeford et al. (2017); Guo et al. (2017)), but also facilitates compliance with the goals of reducing negative impacts to environment and reduces human and environmental risks (Severo et al., 2018). However, even though the adoption of EI is strongly

influenced by ER and financial regulations, it is also true that it is important that government authorities should reform their fiscal system to promote the adoption of EI among manufacturing firms (You et al., 2019).

A third implication of the results obtained is that it has been shown in the literature that ER to be much more effective it has to be rigorous, flexible and enforceable (e.g., Ribeiro and Kruglianskas (2015)), because this would allow a greater implementation of EI in manufacturing firms (Yang and Yang, 2015; Yuan et al., 2017), as ER stimulates the adoption of EI because they essentially reduce the costs for compliance (Dewick et al., 2019), even though the concept of EI is too complex, and requires the application of the three types of knowledge (EI of products, processes and management) to obtain best results (Marzucchi and Montresor, 2017).

A fourth implication derived from the results is that even when empirical evidence has been provided of the positive relationship between ER and EI of products, processes and management (e.g., Cai and Li (2018); You et al. (2019)), there are few studies that analyze and discuss EI from a general point of view, however, the results obtained in this study are consistent and similar to those obtained in the aforementioned studies. Therefore, ER promote, among manufacturing firms, not only the development of the different EI activities of products, processes and management that are more environmentally friendly, but also the significant improvement of SP (Hojnik and Ruzzier, 2016).

A fifth and final implication of the results obtained is that manufacturing firms are increasingly under pressure from different environmental groups, consumers, suppliers, communities and society in general to adopt more effective measures of environmental care sustainable development, so one of the alternatives that are being considered by researchers, academics and industry professionals is EI. However, for manufacturing firms to contribute to reducing the current climate change, they require full compliance with government ER, as this will allow them to significantly reduce the use of energy and raw materials (Fellner et al., 2017), waste (Tisserant et al., 2017), and raw materials (Tisserant et al., 2017).

Table 3. Discriminant validity of the theoretical model

Variables	Environmental Regulation	Eco-innovation	Sustainable Performance
Environmental Regulation	**0.728**	0.045	0.095
Eco-innovation	0.165 - 0.261	**0.609**	0.068
Sustainable Performance	0.244 - 0,372	0.203 - 0.319	**0.642**

The diagonal represents the Extracted Variance Index (EVI), whereas above the diagonal the variance is presented (squared correlation). Below diagonal, the estimated correlation of factors is presented with 95% confidence interval.

4 Conclusions

The results obtained in this study will generate different conclusions among the most important will be the following. A first conclusion is the theoretical model that is considered to have a high internal consistency, generating a strong correlation between the three constructs analyzed, which determines the acceptance of the two research hypotheses proposed. A second conclusion is the same theoretical model used that has an overview of the main EI activities (product eco-innovation, process eco-innovation and management eco-innovation). A third conclusion is many previously published studies that have analyzed and discussed the relationship between ER, EI and SP are few, compared to studies that have been oriented towards conceptualization (You et al., 2019), which from our point of view lack a specific contribution.

A fourth conclusion is that the analysis of the relationship between these three important cons-

Table 4. Results of the SEM

Hypothesis	Structural Relationship	Standardized Coefficient	Robust t-Value
$\mathbf{H}_1$: The higher level of environmental regulations, higher level of eco-innovation.	Environmental R $\rightarrow$ Eco-inn.	0.989^{***}	20.409
$\mathbf{H}_2$: The higher level of eco-innovation, higher level of sustainable performance.	Eco-inn. $\rightarrow$ Sustainable P.	0.265^{***}	14.074

S-BX^2 (df = 214) = 685.502; $p < 0.000$; NFI = 0.901; NNFI = 0.916; CFI = 0.929; RMSEA = 0.069
*** = P < 0,01

tructs is a relatively recent topic in the literature, even though the relationship of these three constructs is increasingly gaining attention of researchers, academics and industry professionals the empirical results are not necessary to establish a total relationship, so it is possible to conclude the relationship between ER, EI and SP is an unfinished issue that is open to discussion (Yuan and Xiang, 2018). A fifth conclusion is that the analysis of the relationship between the three constructs analyzed is this empirical study in emerging economy countries, as is the case in Mexico, has not been explored in the literature, so this study provides empirical evidence and new knowledge of the relationship between the three constructs.

A sixth and final conclusion is that the results of this empirical study affected the generation of knowledge, both from previously published studies that analyzed the effects of ER and EI (e.g. Yuan and Xiang (2018); Dewick et al. (2019); You et al. (2019)), as of those studies that analyze the relationship between EI and SP (e.g. Yuan et al. (2017); **?**); Cai and Li (2018)), by incorporating them into a model that simultaneously analyzes the four types of ER and the three types of EI most cited in the literature, which allows to conclude in general terms that ER do allow a significant increase in EI.

This study has different limitations that are essential to consider before analyzing and interpreting the results obtained. A first limitation of this study is the use of the measurement scales of ER, EI, and SP, since these three important constructs were measured through subjective indicators obtained from the survey. Therefore, in future studies it will be necessary to incorporate some objective data of manufacturing firms (e.g., total certifications in international and national standards, amount of tax payment for emissions of polluting gases, amount of EI performed, percentage of energy use renewable, percentage of treated water use), to verify whether the results obtained differ or not from those obtained in this study.

A second limitation is that ER and EI (EI of products, processes and management), may have better results if they are analyzed and discussed in a disaggregated manner, or if a moderating variable is incorporated into the analysis of the particular characteristics of manufacturing firms (e.g., size, subsector, location), or of managers (e.g. leadership, experience, skills). Therefore, in future studies it will be necessary to use some variables that moderate the effects exerted by ER on EI, and this in their view on SP, to corroborate whether the results obtained are different from the results found in this study.

A third limitation is that this study considered only four types of ER and the three types of EI most cited in the literature, so in future studies it would be necessary to consider other types of EI (e.g., marketing, technology, systems), to corroborate whether the results obtained are similar or not to those obtained in this study. A fourth and final limitation of these results is that the surveys were applied only in the manufacturing firms of the Mexican automotive industry, so in future studies it would be convenient to apply them in other sectors to corroborate whether the results obtained differ or not from the results obtained in this study.

Author Contributions

GMG; Conceptualization, project administration, software, supervision, writing-original draft, writing-revision and editing. RJT; Data curation, formal analysis, research, software, writing-review and editing. VMMM; Conceptualization, formal analysis, methodology, software, writing-review and editing.

References

Achmad, G., Yudaruddin, R., Budiman, P., Santi, E., Purnomo, A., and Wahyuningsih, N. (2023). Eco-innovation and sme performance in time of covid-19 pandemic: Moderating role of environmental collaboration. *Emerging Science Journal*, 7:251–263. Online:https://n9.cl/zhgzl.

Afshari, H., Searcy, C., and Jaber, M. (2020). The role of eco-innovation drivers in promoting additive manufacturing in supply chains. *International Journal of Production Economics*, 223:107538. Online:https://n9.cl/vshn8z.

Al-Hanakta, R., Hossain, M., Pataki, L., and Dunay, A. (2023). Eco-innovation influence on business performance in jordanian micro, small and medium enterprises operating in the food processing sector. *Plos one*, 18(2):e0281664. Online:https://n9.cl/6d7a3w.

Almeida, F. and Wasim, J. (2023). Eco-innovation and sustainable business performance: perspectives of smes in portugal and the uk. *Society and Business Review*, 18(1):28–50. Online:https://n9.cl/3piem.

Anderson, J. and Gerbing, D. (1988). Structural equation modeling in practice: A review and recommended two-step approach. *Psychological bulletin*, 103(3):411. Online:https://n9.cl/p5x3n.

Andersson, M., Moen, O., and Brett, P. (2020). The organizational climate for psychological safety: Associations with smes' innovation capabilities and innovation performance. *Journal of Engineering and Technology Management*, 55:101554. Online:https://n9.cl/e5w6x.

Arranz, N., Arguello, N., and de Arroyabe, J. (2021). How do internal, market and institutional factors affect the development of eco-innovation in firms? *Journal of Cleaner Production*, 297:126692. Online:https://n9.cl/t4n5m.

Aulakh, P. and Gencturk, E. (2000). International principal-agent relationships: Control, governance and performance. *Industrial Marketing Management*, 29(6):521–538. Online:https://n9.cl/dgbtd.

Bagozzi, R. and Yi, Y. (1988). On the evaluation of structural equation models. *Journal of the academy of marketing science*, 16:74–94. Online:https://n9.cl/516v2.

Bentler, P. (2005). *EQS 6 Structural Equations Program Manual*. Encino, CA: Multivariate software.

Bitencourt, C., de Oliveira, F., Zanandrea, G., Froehlich, C., and Ladeira, W. (2020). Empirical generalizations in eco-innovation: A meta-analytic approach. *Journal of Cleaner Production*, 245:118721. Online:https://n9.cl/qo75x.

Brown, T. (2006). *Confirmatory Factor Analysis for Applied Research*. The Guilford Press.

Bryman, A. (2016). *Social Research Methods*. Oxford University Press, 5th edition.

Byrne, B. (2006). *Structural Equation Modeling with EQS, Basic Concepts, Applications, and Programming*. LEA Publishers, 2nd edition.

Cai, W. and Li, G. (2018). The drivers of eco-innovation and its impact on performance: Evidence from china. *Journal of Cleaner Production*, 176:110–118. Online:https://n9.cl/0wgfp.

Chang, P., Cheah, J., and Amran, A. (2021). Eco-innovation practices and sustainable business performance: The moderating effect of market turbulence in the malaysian technology industry. *Journal of Cleaner Production*, 283:124556. Online:https://n9.cl/4q9h0.

Chen, J. and Liu, L. (2019). Customer participation, and green product innovation in smes: The mediating role of opportunity recognition and exploitation. *Journal of Business Research*, 119:151–162. Online:https://n9.cl/yedn9.

Costa-Campi, M., García, J., and Martínez, E. (2017). What are the determinants of investment in environmental r&d? *Energy Policy*, 104:455–465. Online:https://n9.cl/sd29h.

Dewick, P., Maytorena, E., and Winch, G. (2019). Regulation and regenerative eco-innovation: the case of extracted materials in the uk. *Ecological Economics*, 160:38–51. Online:https://n9.cl/ps927.

Emina, K. (2021). Sustainable development and the future generations. *Social Sciences, Humanities and Education Journal (SHE Journal)*, 2(1):57–71. Online:https://n9.cl/l18n9.

Fellner, J., Lederer, J., Scharff, C., and Laner, D. (2017). Present potentials and limitations of a circular economy with respect to primary raw material demand. *Journal of Industrial Ecology*, 21(3):494–496. Online:https://n9.cl/8lr2g.

Fernández, S., Torrecillas, C., and Labra, R. (2021). Drivers of eco-innovation in developing countries: The case of chilean firms. *Technological Forecasting and Social Change*, 170:120902. Online:https://n9.cl/jybhz.

Fornell, C. and Larcker, D. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, 18(1):39–50. Online:https://n9.cl/uxr68.

Forza, C. (2016). *Surveys*, chapter Research Methods for Operations Management, pages 54–73. Routledge, 2nd edition.

Frigon, A., Doloreux, D., and Shearmur, R. (2020). Drivers of eco-innovation and conventional innovation in the canadian wine industry. *Journal of Cleaner Production*, 275:124115. Online:https://n9.cl/q5037.

Gadenne, D., Mia, L., Sands, J., Winata, L., and Hooi, G. (2012). The influence of sustainability performance management practices on organisational sustainability performance. *Journal of Accounting & Organizational Change*, 8(2):210–235. Online:https://n9.cl/sm1r0.

García-Granero, E., Piedra, L., and Galdeano, E. (2020). Measuring eco-innovation dimensions: The role of environmental corporate culture and commercial orientation. *Research Policy*, 49(8):104028. Online:https://n9.cl/h6ycg.

García-Parra, M., De la Barrera, F., Plazas-Leguizamón, N., Colmenares-Cruz, A., Cancimance, A., and Soler-Fonseca, D. (2022). Los objetivos de desarrollo sostenible en américa: Panorama. *La Granja: Revista de Ciencias de la Vida*, 36(2):46–59. Online:https://bit.ly/4aUrvUx.

Geng, D., Lai, K., and Zhu, Q. (2021). Eco-innovation and its role for performance improvement among chinese small and medium-sized manufacturing enterprises. *International Journal of Production Economics*, 231:107869. Online:https://n9.cl/faadc.

Geng, M. and He, L. (2021). Environmental regulation, environmental awareness and environmental governance satisfaction. *Sustainability*, 13(7):1–17. Online:https://n9.cl/izp36k.

Guo, J., Chen, M., Sun, X., Wang, Z., and Xue, J. (2020). Leveraging industrial-technological innovation to achieve sustainable development: A systems thinking perspective. *Plos one*, 15(12):1–23. Online:https://n9.cl/8ss0w.

Guo, L., Qu, Y., and Tseng, M. (2017). The interaction effects of environmental regulation and technological innovation on regional green growth performance. *Journal of cleaner production*, 162:894–902. Online:https://n9.cl/nocu1.

Hair, J., Black, W., Babin, B., and Anderson, R. (2014). *Multivariate Data Analysis*. Pearson Education, 7th edition.

Hair, J., Celsi, M., Money, A., Samouel, P., and Page, M. (2016). *Essentials of Business Research Methods*. Routledge, 3rd edition.

Han, M. and Chen, W. (2021). Determinants of eco-innovation adoption of small and medium enterprises: An empirical analysis in myanmar. *Technological Forecasting and Social Change*, 173:121146. Online:https://n9.cl/qmb1a.

Hojnik, J. and Ruzzier, M. (2016). What drives eco-innovation? a review of an emerging literature. *Environmental innovation and societal transitions*, 19(1):31–41. Online:https://n9.cl/wobsz.

Hojnik, J., Ruzzier, M., and Lipnik, A. (2014). Pursuing eco-innovation within southeastern european clusters. *IUP Journal of Business Strategy*, 11(3):42–59. Online:https://n9.cl/h51ci.

Iverson, R. and Maguire, C. (2000). The relationship between job and life satisfaction: Evidence from a remote mining community. *Human relations*, 53(6):807–839. Online:https://n9.cl/8fpr9.

Kautish, P. and Khare, A. (2022). Antecedents of sustainable fashion apparel purchase behavior. *Journal of Consumer Marketing*, 39(5):475–487. Online:https://n9.cl/c6ulg.

Kraus, S., Rehman, S., and García, F. (2020). Corporate social responsibility and environmental performance: The mediating role of environmental strategy and green innovation. *Technological forecasting and social change*, 160:120262. Online:https://n9.cl/15f36.

Liao, Y. and Tsai, K. (2019). Innovation intensity, creativity enhancement, and eco-innovation strategy: T he roles of customer demand and environmental regulation. *Business Strategy and the Environment*, 28(2):316–326. Online:https://n9.cl/0g4ip.

Liao, Z. (2018). Environmental policy instruments, environmental innovation and the reputation of enterprises. *Journal of Cleaner Production*, 171:1111–1117. Online:https://n9.cl/i08nb.

Long, X., Sun, C., Wu, C., Chen, B., and Boateng, K. (2020). Green innovation efficiency across china's 30 provinces: estimate, comparison, and convergence. *Mitigation and Adaptation Strategies for Global Change*, 25:1243–1260. Online:https://n9.cl/aupxu.

Maldonado-Guzmán, G. and Garza, J. (2020). Eco-innovation practices' adoption in the automotive industry. *International Journal of Innovation Science*, 12(1):80–98. Online:https://n9.cl/54umg.

Marzucchi, A. and Montresor, S. (2017). Forms of knowledge and eco-innovation modes: Evidence from spanish manufacturing firms. *Ecological Economics*, 131:208–221. Online:https://n9.cl/gcdhk.

Mercado-Caruso, N., Segarra, M., Ovallos, D., and Peiró, A. (2020). Identifying endogenous and exogenous indicators to measure eco-innovation within clusters. *Sustainability*, 12(15):6088. Online:https://n9.cl/n6icv.

Michalski, M., Montes-Botella, J., and Guevara Piedra, W. (2023). Eco-innovation and performance of smes in ecuador. *Academia Revista Latinoamericana de Administración*, 36(3):388–406. Online:https://n9.cl/zjqhl.

Muhammad, S., Long, X., and Salman, M. (2020). Covid-19 pandemic and environmental pollution: A blessing in disguise? *Science of the total environment*, 728:138820. Online:https://n9.cl/wtpk7.

Nunally, J.and Bernstein, I. (1994). *Psychometric Theory*. Routledge, 3rd edition.

Pan, X., Ai, B., Li, C., Pan, X., and Yan, Y. (2017). Dynamic relationship among environmental regulation, technological innovation and energy efficiency based on large scale provincial panel data in china. *Technological Forecasting and Social Change*, 144:428–435. Online:https://n9.cl/xyv4q.

Podsakoff, P., MacKenzie, S., Jeong, L., and Podsakoff, N. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. *Journal of Applied Psychology*, 88(5):879–903. Online:https://n9.cl/bek0c.

Podsakoff, P., MacKenzie, S., and Podsakoff, N. (2012). Sources of method bias in social science research and recommendations on how to control it. *Annual review of psychology*, 63:539–569. Online:https://n9.cl/29oe2.

Porter, M. and van der Linde, C. (1995). Green and competitive: Ending the stalemate. *Harvard Business Review*, 73(1):120–134. Online:https://bit.ly/47qYSLw.

Rana, S. and Solaiman, M. (2022). Moral identity, consumption values and green purchase behaviour. *Journal of Islamic Market*, 14(10):2550–2574. Online:https://n9.cl/strq73.

Ribeiro, F. and Kruglianskas, I. (2015). Principles of environmental regulatory quality: A synthesis from literature review. *Journal of Cleaner Production*, 1(96):58–76. Online:https://n9.cl/0a8yg.

Sanni, M. (2018). Drivers of eco-innovation in the manufacturing sector of nigeria. *Journal of Cleaner Production*, 6(131):303–314. Online:https://n9.cl/4hiyph.

Segarra-Oña, M., Peiró, A., and Payá, A. (2014). Factors influencing automobile firm's eco-innovation orientation. *Engineering Management Journal*, 26(1):31–38. Online:https://n9.cl/n4sce.

Severo, E., de Guimarães, J., and Dorion, E. (2018). Cleaner production, social responsibility and eco-innovation: Generations' perception for a sustainable future. *Journal of Cleaner Production*, 186:91–103. Online:https://n9.cl/on7x9.

Shu, C., Zhou, K., Xiao, Y., and Gao, S. (2016). How green management influences product innovation in china: The role of institutional benefits. *Journal of business ethics*, 133:471–485. Online:https://n9.cl/v1gxk.

Singh, S., Del Giudice, M., Chierici, R., and Graziano, D. (2020). Green innovation and environmental performance: The role of green transformational leadership and green human resource management. *Technological forecasting and social change*, 150:119762. Online:https://n9.cl/jv1sg.

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., and Tukker, A. (2017). Solid waste and the circular economy: a global analysis of waste treatment and waste footprints. *Journal of Industrial Ecology*, 21(3):628–640. Online:https://n9.cl/1nmbc.

Tseng, C., Chang, K., and Chen, H. (2021). Strategic orientation, environmental management systems, and eco-innovation: Investigating the moderating effects of absorptive capacity. *Sustainability*, 13(21):12147. Online:https://n9.cl/rgqpa.

Wakeford, J., Gebreeyesus, M., Ginbo, T., Yimer, K., Manzambi, O., Okereke, C., Black, M., and Mulugetta, Y. (2017). Innovation for green industrialization: An empirical assessment of innovation in ethiopia's cement, leather and textile sectors. *Journal of Cleaner Production*, 166:503–511. Online:https://n9.cl/576sg.

Wang, F. (2023). The intermediary and threshold effect of green innovation in the impact of environmental regulation on economic growth: Evidence from china. *Ecological Indicators*, 153:110371. Online:https://n9.cl/magjd.

Wang, J. and Zhang, G. (2022). Can environmental regulation improve high-quality economic development in china? the mediating effects of digital economy. *Sustainability*, 14(19):12143. Online:https://n9.cl/lwxg0.

Wang, Y., Font, X., and Liu, J. (2020). Antecedents, mediation effects and outcomes of hotel eco-innovation practice. *International Journal of Hospitality Management*, 85:102345. Online:https://n9.cl/3u0mo.

Wasiq, M., Kamal, M., and Ali, N. (2023). Factors influencing green innovation adoption and its impact on the sustainability performance of small-and medium-sized enterprises in saudi arabia. *Sustainability*, 15(3):2447. Online:https://n9.cl/bekj5.

Xie, B., Yang, C., Song, W., Song, L., and Wang, H. (2023). The impact of environmental regulation on capacity utilization of china's manufacturing industry: An empirical research based on the sector level. *Ecological Indicators*, 148(1):110085. Online:https://n9.cl/bqx0h.

Xie, R., Yuan, Y., and Huang, J. (2017). Different types of environmental regulations and heterogeneous influence on "green" productivity: evidence from china. *Ecological economics*, 132:104–112. Online:https://n9.cl/teq2l.

Xu, W., Zheng, J., and Liu, C. (2020). Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of chinese cities. *Energy Economics*, 19(1):31–38.

Yang, F. and Yang, M. (2015). Analysis on china's eco-innovations: Regulation context, intertemporal change and regional differences. *European Journal of Operational Research*, 247(3):1003–1012. Online:https://n9.cl/hqicf.

You, D., Zhang, Y., and Yuan, B. (2019). Environmental regulation and firm eco-innovation: Evidence of moderating effects of fiscal decentralization and political competition from listed chinese industrial companies. *Journal of cleaner production*, 207:1072–1083. Online:https://n9.cl/6e0x4y.

Yuan, B., Ren, S., and Chen, X. (2017). Can environmental regulation promote the coordinated development of economy and environment in china's manufacturing industry? a panel data analysis of 28 sub-sectors. *Journal of cleaner production*, 149:11–24. Online:https://n9.cl/gwt23w.

Yuan, B. and Xiang, Q. (2018). Environmental regulation, industrial innovation and green development of chinese manufacturing: Based on an extended cdm model. *Journal of cleaner production*, 176:895–908. Online:https://n9.cl/dl4pc.

Yurdakul, M. and Kazan, H. (2020). Effects of eco-innovation on economic and environmental performance: Evidence from turkey's manufacturing companies. *Sustainability*, 12(8):3167. Online:https://n9.cl/4xmgu.

Zhang, Y., Sun, J., Yang, Z., and Wang, Y. (2020). Critical success factors of green innovation: Technology, organization and environment readiness. *Journal of Cleaner Production*, 264:121701. Online:https://n9.cl/2vfc5.

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Carihuairazo glacier retreat and its perception in the Cunucyacu community

Retroceso del glaciar del Carihuairazo y sus implicaciones en la comunidad de Cunucyacu

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Abstract

The retreat of glaciers is a reality throughout the Andes Mountain range, especially in low-altitude mountains. One of these cases is the loss of the remaining ice mass in Carihuairazo (Tungurahua, Ecuador), which in recent years has experienced a considerable retreat. This research aims to characterize the retreat of this glacier and its implications for the nearby community (Cunucyacu) through the application of a multi-source methodology, which includes the collection of glacier aerial photographs, data from nearby meteorological stations, the use of global climate reanalysis data, interviews with community members, and mountaineers who work and frequent the area. To characterize the glacier's mass evolution, a hydroglaciological model was applied, using input data from meteorological series, and its parameters were calibrated with the photographic record of the glacier's outline. The results show a glacier loss of 99 % of its surface in 1956 (0.34 km^2) by 2021. The model successfully simulates the glacier area variation over 67 years, revealing a continuous decrease since 1978, with short periods of recovery and equilibrium, where temperature is the variable that best explains the glacier's retreat. However, the model fails to consider the effect of external factors, such as the eruption of the Tungurahua volcano that could enhance the glacier retreat. The Carihuairazo glacier is in a situation of inevitable disappearance, highlighting the vulnerabilities of communities facing this phenomenon as a consequence of climate change.

Keywords: Glacier retreat, glacier, hydroglaciological model, climate change, Carihuairazo, Cunucyacu.

Resumen

El retroceso de los glaciares es una realidad en toda la cordillera de los Andes, sobre todo en montañas de baja altitud. Uno de estos casos es la pérdida de la masa de hielo remanente en el Carihuairazo (Tungurahua, Ecuador), que en los últimos años ha experimentado un retroceso considerable. En esta investigación se intenta caracterizar el retroceso de este glaciar y su implicación en la comunidad más cercana (Cunucyacu) por medio de la aplicación de una metodología de múltiples fuentes que incluye la recopilación de aerofotografías del glaciar, datos de estaciones meteorológicas cercanas, uso de datos de reanálisis del clima global, entrevistas a miembros de la comunidad y a andinistas que trabajan y frecuentan la zona. Para caracterizar la evolución de la masa del glaciar aplicamos un modelo hidroglaciológico que usa como entrada datos de series meteorológicas y cuyos parámetros fueron calibrados con el registro fotográfico del contorno del glaciar. Como resultados se puede evidenciar una pérdida del glaciar para el 2021 equivalente al 99 % de su superficie en 1956 (0.34 km^2). El modelo logra simular la variación del área del glaciar durante 67 años, en donde se observa un decrecimiento continuo del glaciar a partir de 1978, con cortos periodos de recuperación y equilibrio, en donde la temperatura es la variable que mejor explica el retroceso del glaciar. El modelo no logra considerar el efecto de factores externos como el caso de la erupción del volcán Tungurahua que podría favorecer el retroceso del glaciar. El glaciar Carihuairazo se encuentra en una situación de inevitable desaparición y revela las vulnerabilidades de las comunidades que se enfrentan a este fenómeno como consecuencia del cambio climático.

Palabras clave: retroceso glaciar, glaciares, modelo hidroglaciológico, cambio climático, Carihuairazo, Cunucyacu.

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1 Introduction

Glaciers play a significant role in the sustainability of ecosystems and the environmental balance of the regions where they are located, as in the moors (Aguilar-Lome et al., 2019; García, 2022). Glaciers act as water reservoirs, affecting all aspects related to their use, both for irrigation and consumption, in addition to their use for mining and hydroelectric generation processes (Vuille, 2013; Naranjo-Silva, 2024). The decrease in water flows associated with glacial retreat causes scarcity and generates conflicts for the rights of use between the inhabitants of mountain areas and companies that want to control access to water (Vuille, 2013). In addition to contributing to water supply, regulating the climate and maintaining a habitat for biodiversity, for Vilela (2011), they influence in the culture, identity, imaginaries and tourism.

The Carihuairazo is an extinct stratum of volcano located in the Western Cordillera of Ecuadorian Andes. The glacier contributes to several tributaries, but mainly to those located towards the eastern flank of the mountain. One of the closest populations to the glacier is the community of Cunucyacu, belonging to the parish Pilahuín, southwest of Ambato in the province of Tungurahua, in the central area of Ecuador and located north of the Carihuairazo. Currently, in the community there is a decrease in the amount of water originated in the mountain. Considering the previous studies of Cáceres and Cauvy (2015), the setback of Carihuairazo has been observed since 2003, and this process points towards its inevitable extinction (Francou et al., 2011), which could occur in the coming years. Postigo (2013) highlights the interest of knowing the impact of the glacial retreat from the perspective of the various actors involved in underlying conflicts, each of them with interests and priorities different and opposed to each other. In this sense, the testimonies and perception of different actors in this environment, as well as social agents involved with conservation experiences, are valuable.

Over the last decades, glaciers around the world have experienced a reduction in their volume (Bahr and Peckham, 1997; Basantes, 2010; Condom et al., 2011; Favier et al., 2008; Hugonnet et al., 2021). Glacial retreat is defined by Johansen et al. (2019) as the inability to store water during cooler periods and release them in the form of melt fluid during the dry season. 99% of the world's tropical glaciers are located in the Andes (Condom et al., 2011), the same ones that have experienced a negative mass balance of $0,42 \pm 0,24$ m/year (Dussaillant et al., 2019), and there is evidence with satellite imagery and aerial photography (Basantes, 2010; Condom et al., 2011). This rapid retreat has caused global concerns about the availability of water resources, as a consequence of climate variability (French et al., 2016).

Considering the effect of climate change, there is a need to raise awareness in populations near glaciers about changes in climate patterns, and their socio-environmental consequences, since as proposed by Rhoades (2008), there is a better understanding of the urgency for adopting community mitigation and adaptation strategies that involve and favor local farmers against new climate scenarios (Pacheco-Peña et al., 2023), taking into account the need to preserve the moors as an ecosystem sensitive to glacial retreat, as pointed out by Cabrera and Romero (2013), in its qualitative assessment of the vulnerability to climate change of the main ecosystems of the Metropolitan District of Quito.

Volume changes in tropical glaciers are subject to atmospheric conditions (Favier et al., 2008; Sicart et al., 2008), glacier morphological conditions and topographic conditions (Vuille, 2013). Precipitation is stored as snow and ice, contributing to glacier mass accumulation (Favier et al., 2008). Melting is controlled by the variation of energy flows from the atmosphere, such as turbulent flow influenced by the temperature gradient between air and ice; and latent flow influenced by humidity (Sicart et al., 2008). There is also a correlation between temperature and melting in glaciers (Sicart et al., 2008). In the case of a sustained retreat of a glacier, the main feature of this phenomenon is the melting of the huge ice masses without the possibility of regenerating (Sandoval, 2021). For analyzing this phenomenon in tropical glaciers, Ramírez (2008) mentions among its main causes variations in climatic patterns such as precipitation and temperature, since, if there is no coincidence of precipitation and low temperatures, it is not possible to form permanent snow that renews and maintains the cycles of water regulation associated with glaciers. However, this is a complex multi-variable phenomenon, which is not controlled only by the amount of rainfall and temperatu-

re, but is also influenced by factors such as albedo, orientation, slope, among others. For example, ash deposition on the glacier caused by volcanic eruptions can change the albedo coefficient, altering the energy balance (Salcedo, 2019).

Various models have been developed to simulate volume variation in glaciers. The ITGG-2.0 model proposed by Juen (2006), is based on a vertical mass profile, where the density change is calculated as a function of altitude. In this model, the energy variation from altitude is based only on albedo and temperature gradients. In addition, a complete energy balance is performed including the estimation of latent and sensitive turbulent flows. On the other hand, the WEAP model proposed by Condom et al. (2011) is broader. Unlike the previous model, it does not employ a complete energy balance that considers all glacier processes, which requires detailed data and complicated calculations. Instead, the model divides the area of the basin into strips of height, some without a glacier, others with and without a glacier, and others completely with a glacier. The total volume is determined from the interactions between these bands. A more general model is the ICE-KISS model proposed by Pouget (2011), which considers a dynamic division of glaciers based on a temperature limit in the accumulation and ablation zones. In this way, sublimation and other explanatory variables are taken into account. The model uses a separation of areas of the glacier in accumulation zone and ablation zone (which is subdivided into high and low), being the main difference the temperature. In the country, several empirical and physical models have been proposed that have addressed the past and future of glaciers depending on the climate and the morphological conditions where the glacier is located. There are several models to evaluate 15th glacier of Antisana (Cáceres et al., 2006; Basantes-Serrano et al., 2016) and 12 of Antisana (Gualco et al., 2022) and a model of glacial dynamics to evaluate the state of the entire ice cap. Domínguez et al. (2012), proposed a model for the 15th glacier of Antisana.

This research aims to characterize the retreat of the Carihuairazo glacier through the use of a hydroglaciological model, a photographic record and the analysis of the influence of climatic factors and external factors. Additionally, it is intended to analyze the problems derived from the glacial retreat of Carihuairazo, considering the perception of climbers and other social agents who live or work in this area. In this sense, it is intended to confront the scientific information that validates the physical loss of the glacier thanks to hydrological and glaciological works, with the perception of some inhabitants and other social actors working in the area.

2 Materials and methods

2.1 Glacial surfaces

The area of the research corresponds to the Carihuairazo volcano and the Cunucyacu community (Figure 1), belonging to the Pilahuín parish. This community is located at an altitude of 4057 m.a.s.l. and 9.25 km from the Carihuairazo volcano. Carihuairazo is geographically located at the coordinates 1°2425S 78°4500W and reaches an elevation of 5018 m.a.s.l. It is a stratovolcano that collapsed towards the WNW (West-Northwest), located 10 km northwest of the Chimborazo volcano and 35 km from the Tungurahua volcano. The date of its last eruption is unknown, however, Clapperton (1990) points out that it may have occurred eleven thousand years ago. Rivers (Figure 1) emerge from the moors of Carihuairazo, which will irrigate arid areas of the provinces of Tungurahua and Chimborazo. This is where the Blanco River originates, which downstream joins the Colorado or Pucuyacu River, which forms the Ambato River by descending through the Chimborazo sandwaters (Moreno, 2023).

2.2 Meteorology

To characterize the glacial retreat of Carihuairazo and to know the perception of the Cunucyacu community to its extinction, we have used a methodology from multiple sources as Rhoades (2008), did in his study on the disappearance of the glacier of Cotacachi, including: repetitive photographs, data from weather stations, interviews to members of the Cunucyacu community and climbers who work and frequent the area, interviews to social actors with conservation experiences of moors since the 1970s. In this study we have collected different mea-

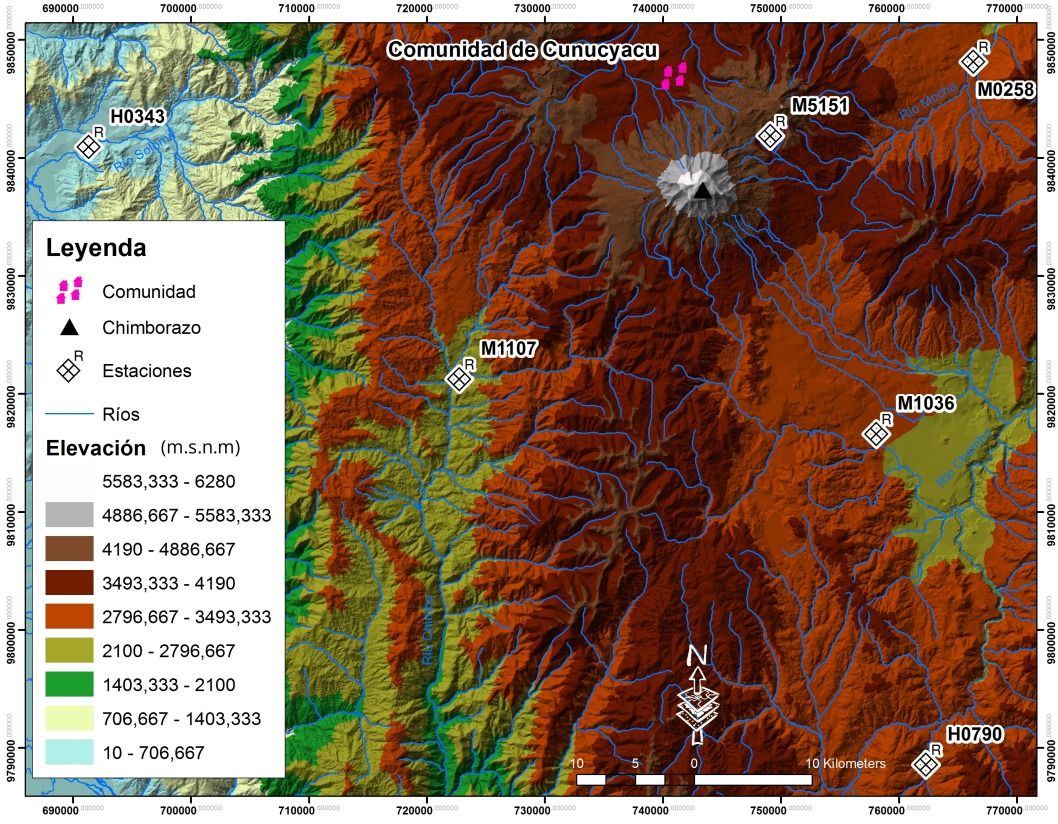

Figure 1. Map of the study area corresponding to the Carihuairazo glacier, location of the community of Cunucyacu and drainage of water sources in the community of Cunucyacu. Additionally, the location of the weather stations closest to the glacier is identified. Source: Digital Terrain Model (DTM) of Ecuador.
Source: Sigtierra Metadata Catalog.

surements of the glacier since 1956, considering the previous works ofCáceres and Cauvy (2015). This glacial contour was the reference to compare the percentage of loss until now. To complement this information, a photographic record of the mountain since the 1950s was also compiled. We also have meteorological data provided by the INAMHI (National Institute of Meteorology and Hydrology) stations closest to the study areas. Finally, to contrast the meteorological information with the perception of the population involved, as La Frenierre and Mark (2017) did in the study of the Chimborazo deglaciation, we also conducted interviews with the leaders of the community of Cunucyacu, climbers who frequent the area and social agents involved with preservation experiences. Likewise, we are interested in relating the climatic variables with the volcanic activity of Tungurahua and its influence on the evolution of the Carihuairazo glacier.

2.2.1 Glaciological data

The oldest data is the surface of the Carihuairazo glacier in 1956, which then reached an area of 0.34 km^2, from there we consider the measurements of the glacial contour made by Cáceres and Cauvy (2015); Villacis (2008) and Rosero et al. (2021). In addition, an updated measurement was made to contrast with the available measurements since its first monitoring in 2003. In the data, there is a gap of information between the year 2010 and 2015.

2.2.2 Climate data and *on-site weather* instrumentation

The meteorological data were provided by stations belonging to the National Institute of Meteorology and Hydrology (INAMHI). The "Glaciar 11 Chimborazo" station (M5151), located on the southwestern flank of the Carihuarizo at 1 km and at an

altitude of 4428 m.a.s.l., was used as a reference for studying the glacier. For the treatment of temperature data station "Querochaca" (M0258) was used, located in the canton Cevallos at an altitude of 2865 m.a.s.l. The precipitation data were obtained from stations M0258, M1107 (Laguacoto) and M1036 (Riobamba Polytechnic) at a distance of 18, 35 and 28 km from station M5151, respectively. The validation and data filling process for the reference station included: homogeneity tests, linear regression and orthogonal regression, using distance as a weighting (Guijarrom, 2023).

In order to run the model from the year in which the first record of its surface is held (1956), data from the fifth generation of ERA5 reanalysis (Hersbach et al., 2020) from 1956 to 2022 were used. This information was calibrated to the observed data of the reference station by means of a statistical de-scaling from the calibration of the cumulative probability distribution of the variable with respect to a gamma distribution. From the calibration, the error corresponding to the reanalysis data was estimated.

Data on relative humidity and wind speed are scarce in these four seasons (especially for the years before 2010), for that reason data from the ERA5 reanalysis was used with their respective error (Hersbach et al., 2020).

2.2.3 Volcanic activity of Tungurahua

The Tungurahua volcano is located 35 km from Carihuairazo, its recent volcanic activity was affected with ash deposition on the glaciers of Carihuairazo and its neighbor Chimborazo. The opaque surface produced by the ash layer can affect the albedo values of ice masses, contributing to the melting process.

The eruptive process of Tungurahua began in 1999 and continued until 2016. According to reports from the Geophysical Institute of the (Instituto Geofísico de la Politécnica Nacional, 2015) and the newspaper (El Comercio, 2009, 2016). For more than 16 years, the eruption process of the Tugurahua volcano was permanent and affected several areas of the central region of Ecuador, especially the provinces of Chimborazo and Tungurahua, mainly because of the continuous emission of ash, which damaged agriculture, livestock and even involved at some point the evacuation of nearby populations.

2.3 Hydroglaciological model

The hydroglaciological model used to simulate the variation of the volume of the Carihuairazo glacier is a simplification of the model made by Piedra (2021) in Antisana. The model calculates the variation of the glacier volume monthly from an energy balance that is made with vertical profiles of the mass variation at different altitudes. Unlike other more complex models where a hydrographic basin with a glacial surface is considered and the flow produced by the non-glacial glacier assembly is estimated (Fernádez, 2018; Piedra Santillan, 2021), this model is limited to the glacier. A dynamic division of the glacier is considered for applying the model, which depends on a temperature limit in the area of accumulation and ablation. The equilibrium height line (EHL) represents the height separating the two zones (Juen, 2006).

2.3.1 Change in glacial volume

The model is applied to an annual (i) and monthly timescale (j). The relationship between volume and area of the glacier is given by the equation (Bahr and Peckham, 1997):

$$Ag_i = \left(\frac{Vg_i}{c}\right)^{1/b} \tag{1}$$

Where Ag is the area of the glacier, Vg is the volume of the glacier ab, c Vg is the calibration constants (section 2.3.5). The variation in glacial volume (ΔVg) for a given year is given by:

$$\Delta Vg_i = (\Delta Vab_i + \Delta Vac_i)\,\frac{\rho_a}{\rho_h} \tag{2}$$

Where ΔVab is the volume variation in the ablation zone, ΔVac is the volume variation in the accumulation zone, ρ_a and ρ_h are the density of water and ice, respectively.

2.3.2 Ablation zone

The ablation zone is divided into two zones with different contributions, the high (↑) and low (↓) zone, the delimitation of the zones is explained in section 2.3.4. The variation in the ablation zone is estimated from the monthly sum in one year, the total precipitation volume (Vp_{ab}), the melting volume (V_{der}) and the sublimation volume (V_{sub}):

$$\Delta Vab_i = \sum_{j=1}^{12} (V\,p_{ab\,j} - V_{der\,j} - V_{sub\,j}) \quad (3)$$

Precipitation and sublimation volume are estimated by multiplying the ablation area by precipitation and sublimation height, respectively. It should be emphasized that these terms are calculated separately for their use in equation 3. The monthly sublimation was estimated with an empirical relationship considering the latent heat turbulent flow that depends mainly on wind speed and humidity (Francou et al., 2004):

$$Sn_j = a * u_j * (q_j - qs_j) \quad (4)$$

Where a is a constant for the homogeneity of the equation, u is the average monthly wind speed in m/s, q is the specific humidity and qs is the specific humidity for the ice or snow surface under melting conditions in each month. The calculation of specific humidity is based on the methodology proposed by Pouyaud et al. (1995).

For the case of the melt volume, its estimation is the sum of the melt volume in the high and low ablation zone:

$$V_{der} \uparrow\downarrow_j = F_j * M_{ab} \uparrow\downarrow_j * A_{ab} \uparrow\downarrow_j \quad (5)$$

Where F is a correction factor that depends on the variation of the incident radiation by geographic position, azimuth and slope,$M_{ab} \uparrow\downarrow$ is fusion in the high and low ablation zone, and $A_{ab} \uparrow\downarrow$ is the high and low ablation area. For the case of the Carihuairazo glacier, from the slope distribution analysis and the altimetry of the mountain, a constant slope of 25° and an azimuth of 270° have been estimated. The correction factor is estimated as the monthly incident radiation for the average incident radiation, regardless of cloud cover because no data are available. Melting is calculated as a function of temperature, where melting will only occur if the temperature in the zone is higher than the melting limit temperature:

$$M_{ab} \uparrow\downarrow_j = max\{0(a_h \uparrow\downarrow)(T_{ab} \uparrow\downarrow_j - T_{lim} \uparrow\downarrow)\} \quad (6)$$

Where a_h is the melting constant, T_{ab} is the temperature and T_{lim} is the limit temperature in the high and low ablation zone, respectively. The melting constants of each zone were calibrated (section 2.3.5). The limit temperature $T_{lim} \uparrow$ (separates the ablation zone from the accumulation zone) used has been $-1°C$ and for $T_{lim} \downarrow$(separates the ablation zone in high and low) $0,5°C$ (Favier et al., 2004; Francou et al., 2004; Pouget et al., 2017). According to Favier et al. (2004), these thresholds represent the best correlation between daily accumulated snow values and albedo variation for the case of Antisana. For the monthly case, the temperature threshold separates precipitation in liquid and solid state (Francou et al., 2004).

2.3.3 Area of accumulation

The volume variation in the accumulation zone is estimated from the difference between precipitation and sublimation, since there is no melting in this zone. The equation is as follows, where S_{ac} is sublimation in the accumulation zone and Aac is the area of the accumulation zone.

$$\Delta V_{acumi} = \sum_{j=1}^{12} (P_j - S_{ac\,j}) * Aac_j \quad (7)$$

2.3.4 Limit of altitudes, areas and temperatures

The limit altitudes are important variables that allow the dynamic division of the glacier in the three zones (accumulation, high and low ablation). The upper limit height (separates the accumulation and ablation zone) and the lower limit height (separates the upper and lower ablation zone) are estimated with:

$$H_{lim} \uparrow\downarrow_j = \frac{T_{lim} \uparrow\downarrow - T_{ref\,j}}{\Delta T} + H_{ref} \quad (8)$$

Where T_{ref} is the air temperature at the reference station, H_{ref} is the altitude of the reference station and ΔT is the temperature gradient relative to altitude, which is associated with variations in atmospheric circulation and relative humidity availability (Villacis, 2008). This gradient is in the order of -0,77°C,100 m^{-1} to -0,31°C,100 m^{-1} for the levels of 500 and 600 hPa (Villacis, 2008). The temperature gradient used in the model was -0,34°C,100 m^{-1}, obtained from the stations and adjusted to the glacier. This value is similar to -0,35°C,100 m^{-1} used by Pouget (2011) in the Paute basin (Ecuador).

Using the evidence of the glacier contour with the height limit of the extent, the area of the different zones of the glacier was estimated from a polynomial function with respect to elevation. Using the

equation, the area of direct accumulation zone (*Aac*) and the area to the separation of the high and low ablation zone (*Aacab*) are determined. Where the areas of the high and low ablation zone are determined with:

$$Aab\uparrow_j = Aacab\uparrow_j - Aac_j \tag{9}$$

$$Aab\downarrow_j = Ag_i - Aacab\uparrow_j \tag{10}$$

Finally, the temperature in the high and low ablation zone for calculating the fusion is calculated by estimating a mean height in each zone and using a polynomial function that relates the temperature with respect to the elevation.

2.3.5 Calibration of the parameters of the glaciological model and estimation of uncertainty

The glaciological model requires four parameters for its calibration (a, b, $a_h\uparrow$, $a_h\downarrow$). Both the parameters of the glacier area-volume relationship, as well as the melting constants of each zone were calibrated using as an objective function the Nash-Sutcliffe estimator between the available annual observations of the glacier area and the model simulation from a Newton second order optimization method (Byrd et al., 1995). For calibration, calibrated weather series of the reanalysis and the values observed at the reference station were used. These parameters are called model reference parameters.

To estimate the uncertainty regarding the annual area of the glaciological model, the following procedure was performed. First, 10000 series of monthly data for each input weather variable were generated randomly. For each endpoint and each month, the value was generated randomly following a normal distribution with a mean equal to the calibrated value of the reanalysis or the observed value of the endpoint and with a standard deviation corresponding to the error between the calibrated values of the reanalysis and the observed values of the reference station. For each set of series generated, calibration of the parameters of the glaciological model was performed. Subsequently, the model was run with calibrated series of reanalysis and all calibrated parameter sets (10000) were used to demonstrate the influence of calibrated parameters in the model. Finally, the 10000 runs of the model were performed again with the different sets of weather series using the reference parameters. In this sense, it was intended to evaluate the effect of uncertainty of the input data of the model.

2.4 Community perception

The present study confronts the scientific information that validates the physical loss of the glacier thanks to hydrological and glaciological works with the perception of the communities of the area. To do this, we resorted to semi-structured interviews addressed to two members of the community of Cunucyacu. We participated in a general assembly of the whole community, we interviewed eight guides and climbers who frequently visit this mountain, in this way we recorded and compared their observations and perceptions on the retreat of the Carihuairazo glacier in the last thirty years. We also interviewed seven socio-environmental actors related to the care of the wasteland that broadened the view of this situation and its implications.

The community welcomed us at its general assembly, held on September 11, 2020. The 56 participants of this meeting expressed that their main concern regarding this phenomenon is limited to a possible decrease in visitors to the place. On the other hand, they consider that water was not lacking since the time of their grandparents, and although the retreat of the glacier is evident to them, they trust that the loss of the Carihuairazo glacier will not affect them significantly, and would have no problems in the future associated with water management in the area. Climate change and its consequences are not a relevant problem in their discussions.

Interviews were also conducted with several members of the community of Cunucyacu, such as Mr. Luis Punina, who is a community guide of Cunucyacu. The other interview was held on September 1, 2020. The other interview was held on September 11, 2020 to the five members of the community board. The interview of Mr. Segundo Enrique Punina (President of the council of the Cunucyacu community) was done on September 16, 2020. Both the community members and the eight climbers interviewed agree on the dramatic glacial retreat in Carihuairazo. Their concerns and motivations may be different but they refer to the same origin of the problem, the loss of the ice mass, leaving a serious trauma in their perception of this environment, fewer tourists, more dangers on the ascent routes, less

water availability, and uncertainty about a future without glaciers in the Andes.

3 Results and discussion

3.1 Results

3.1.1 Rainfall and temperature timeseries

A good correlation was determined between the meteorological stations used in the study. The correlation coefficient reached a value of 0.67 and 0.82 for precipitation and monthly temperature, respectively. From the validation process and data filling with meteorological stations, the precipitation series was defined in the reference station from 2002 to 2017. For temperature, the series was defined from 1995 to 2012 (Figure 2). Regarding the calibration with the data of the ERA5 reanalysis, statistical de-escalation produced a reconstructed series from 1956 to 2022 for precipitation and air temperature (Figure 2). The correlation coefficient between the calibrated reanalysis series and the reference station was 0.59 and 0.74 for precipitation and temperature, respectively.

3.1.2 Climatic conditions on the glacier

The annual variation of precipitation and temperature in the study area can be seen in Figure 3. Precipitation varies between 458 and 1281 mm and the average is 770 mm. No trend can be seen in the temporal variation of precipitation (positive percentage variation factor of 3%). The wettest years are 1983, 1984, 1994, 1998, 2008 and 2017. On the contrary, the driest years are 1961, 1962, 1986, 2003, 2009 and 2013. Regarding temperature, the average value is $0{,}7^{\circ}$ and ranges from $-0{,}3$ to $1{,}7^{\circ}C$. Unlike precipitation, temperature has a clear positive trend (percentage variation factor of 137%). Excepting 1998, the warmest year is 2013.

3.1.3 Glacier boundary between 1956 and 2021

There are barely 12 records of the contours of Carihuarizo glacier between 1956 and 2021 (Figure 4). The records are based on aerial photographs and topographic measurements, especially from 2003 onwards. There is only one previous record (1956). A downward trend in the glacier's surface area has been identified from the first estimate for the year 1956. This surface will be considered as reference for future estimates of the glacier contour for both photographic records and model outputs. By 2003, the glacier had already lost 30% of its reference area. Unfortunately, there is an information gap between 1956 and 2003, so it cannot be observed if there were recovery periods of the glacier. By 2015, it was already recording a 90% loss compared to 1956. In 2017 and 2021, glacial loss reaches 96% and 99%, respectively.

Figure 4 was elaborated thanks to the photographic archive of the mountaineer Marco Cruz, in which we show the temporal sequence of the glacial retreat in Carihuairazo. According to the definition of the Chilean National Glacier Strategy (CECS, 2009), a glacier is an ice mass of at least 0.1 km^2 in length. If we consider that in 2017 the measured area is 0.015 km^2, confirming that the remaining ice mass can no longer be considered as a glacier.

3.2 Modeling of the Carihuairazo Glacier

The model was run from 1956 to 2022 and its results can be seen in Figure 6. The model shows the recovery of the area of the glacier from 1956 to 1963, followed by a stagnation period of several years and then a significant increase between 1973 and 1976. Starting this year, the glacier is showing a continuous retreat over time, with few recovery periods. It can be observed that the model satisfactorily simulates the evolution of the glacier area until 2010. The model captures the general decreasing trend and variations in the area, including the recovery of the glacier mass in 2008. For this period, the Nash-Sutcliffe (nse) estimator is 0.82 and the mean square error (rmse) is 0.01 km^2. However, the model fails to simulate the glacier area in 2015, 2017 and 2021. Considering the whole period, the nse and rmse reach a value of 0.77 and 0,03 km^2, respectively.

The uncertainty associated with the input variables and model parameters are represented in Figure 6. The smallest range corresponds to 10000 model

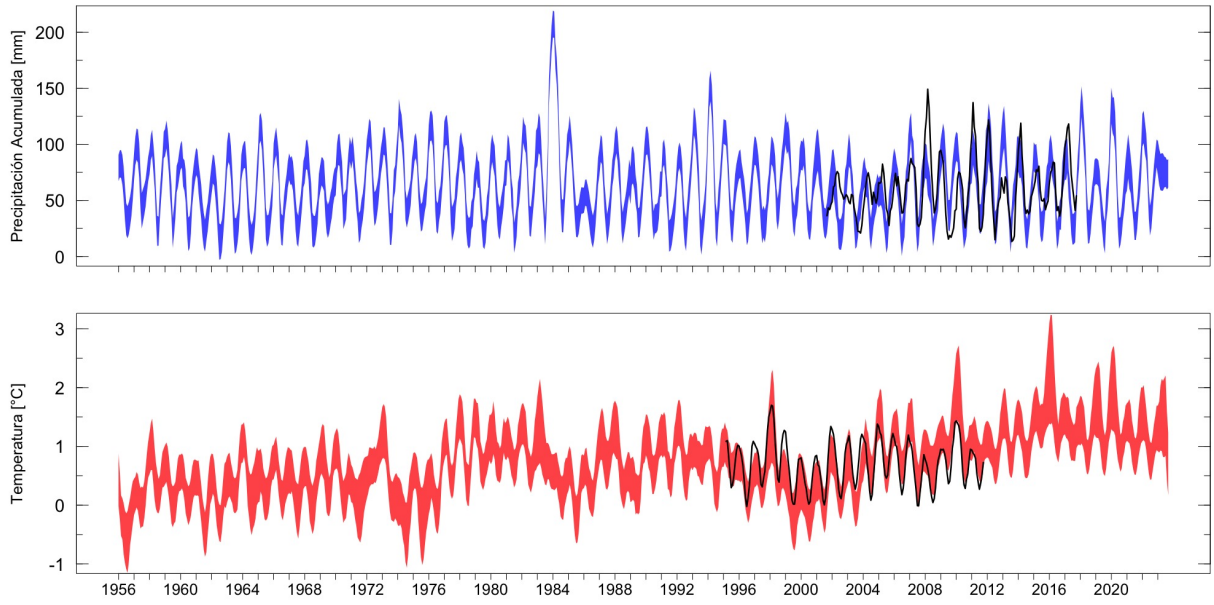

Figure 2. Monthly Precipitation (blue surface) and mean temperature (red surface) for a 95 % confidence interval in the area near Carihuairazo glacier after calibrating ERA5 reanalysis data with observations of the reference station (black line) within the period 1956 to 2022.

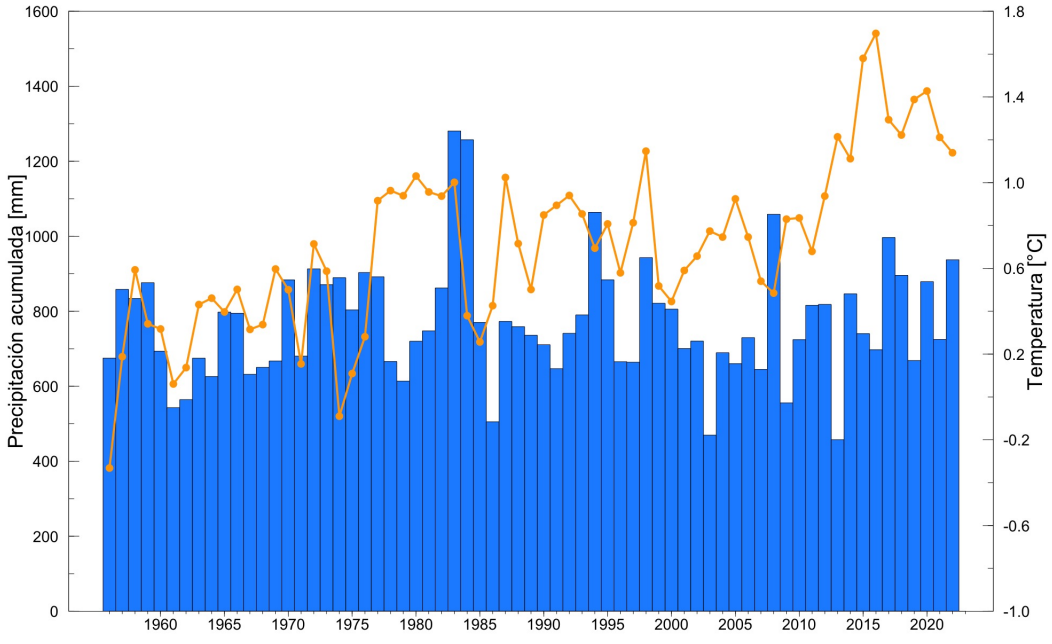

Figure 3. Accumulated precipitation (blue bars) and mean temperature (orange line) in the area near the Carihuairazo glacier in the period 1956 to 2022 obtained from the calibration of the ERA5 reanalysis data with the reference station.

simulations with changes in input variables using calibrated model reference parameters (Table 1). In this case, the band increases in size in relation to the years, and that the greatest uncertainty is seen in the last two decades. The second larger range corresponds to 10000 model simulations with calibrated parameters for each of the 10000 sets of input variables.

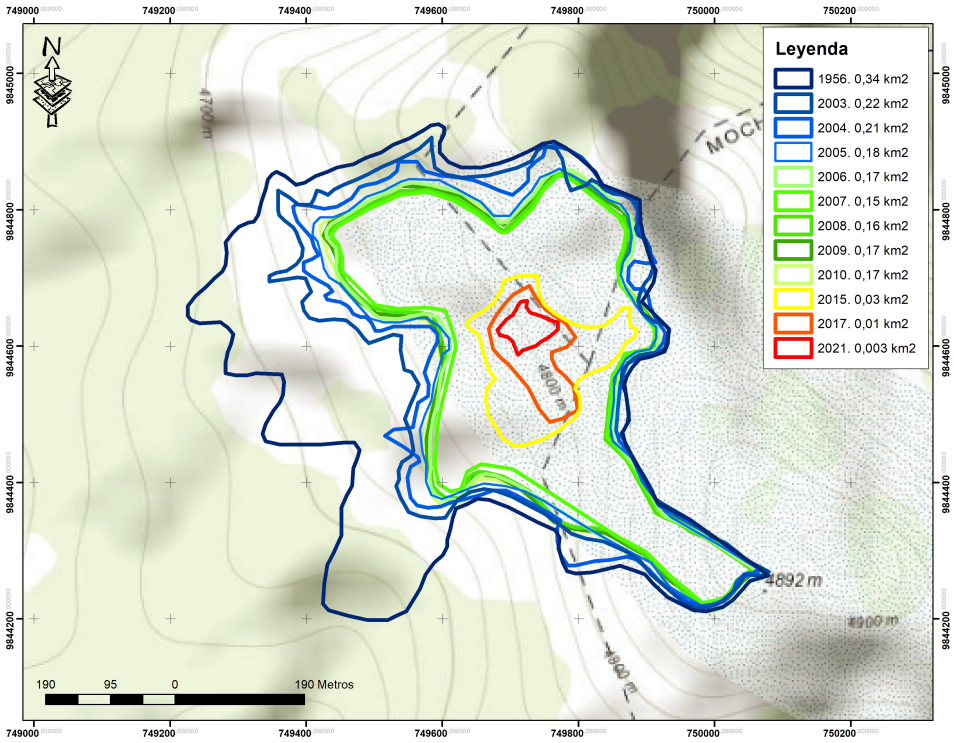

Figure 4. Map of the study area showing the evolution of the glacial retreat of Carihuairazo. The contours of the glacial surface were first measured in 1956 through aerial photographs. There are different topographic field measurements from 2003 to 2021, carried out by different research teams, which reveal the decrease of this ice mass. The blue outer contour shows the area considered as a reference recorded in 1956. On the other hand, the red polygon illustrates the last field measurement made in 2021. Source: Adaptation of Cáceres and Cauvy (2015) and Rosero et al. (2021).

In this case, it can be seen the greatest uncertainty in the first 25 years and in the last 7 years of the simulation. The range of uncertainty between the 1980s and 2010 is similar to that of the first range. Regardless of the combination, it can be seen that the model clearly simulates the loss of mass of the glacier, which increases from the second part of the 80s.

Table 1. Calibrated hydroglaciological model parameters. The range corresponds to 95 % of the 10000 values around the median.

Parameter	Range	Calibrated value
a	0.013 - 0.028	0.014
b	1.27 - 2.01	1.35
$a_h \uparrow$ [mm/month/°C]	214 - 234	218
$a_h \downarrow$ [mm/month/°C]	227 - 328	228

The model allows estimating the input and output variables of the glacier that increase and reduce the size of the glacier, respectively. Figure 7 shows these variables in the run period of the model. The predominant variable is fusion, being the highest variable in 58 % of the time. Precipitation is the highest variable on 28 occasions, being 69 % before 1980 and only on one occasion after 2000. The sublimation is low in relation to the other variables, oscillating around 100 mm of water equivalent height. In relation to the balance between inflows and outflows, there is a deficit in 61 % of the time. This explains the loss of glacier mass that is evident in the variation behavior of the glacier area, where a recovery can be observed in a few years

3.3 Discussion

3.3.1 Hydroglaciological model and influence of climatic and external factors

The hydroglaciological model was run since 1956, corresponding to the first available measurement of the glacier. To complement the data of the cli-

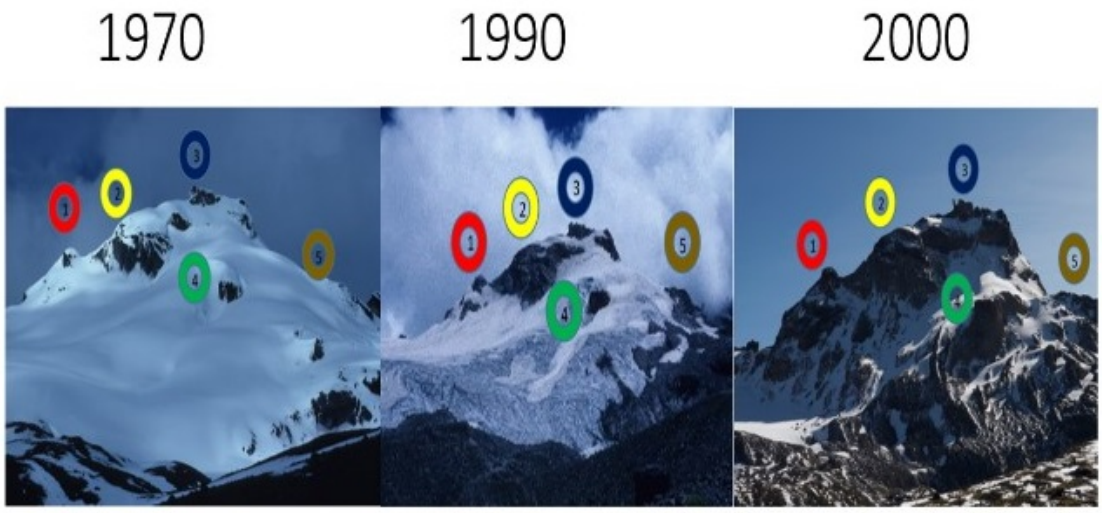

Figure 5. Photointerpretation. The images correspond to the same perspective of the central summit of Carihuairazo, from the southern flank belonging to the Marco Cruz archive. The circles of the same color show the same point on the mountain and how it has varied from the 1970s to the early 2000s. The changes in the mountains in the five reference points considered during the last decades of the 20th century can be seen. Today, the glacier can be considered practically extinct.
Source: Personal collection of Marco Cruz.

matic variables, the product of the reanalysis ERA5 was used. Reanalysis data have been used in other studies in the region such as the case of the Antisana volcano (Bradley et al., 2009; Manciati et al., 2014; Basantes-Serrano et al., 2022). Manciati et al. (2014) found that the variables of the NCEP-NCAR reanalysis (Kalnay et al., 1996) combined with data from regional stations have a good correlation with glacial mass loss. Basantes-Serrano et al. (2022) used the ERA5 reanalysis to estimate the effect of climate and topography on the variation of Antisana volume, where it was found that the reanalysis series was able to capture the seasonality of precipitation and temperature on the west side of the volcano. In this study, ERA5 reanalysis was used because it showed a better correlation with the reference station for temperature than NCEP-NCAR reanalysis.

The reconstituted temperature series presents a clear positive trend that magnified more from the year 2012. This trend is in accordance with results obtained at global (Hugonnet et al., 2021; Intergovernmental Panel on Climate Change (IPCC), 2022) and regional levels (Morán-Tejeda et al., 2016; Aguilar-Lome et al., 2019; Imfeld et al., 2021). The temperature shows an increase of $0{,}14°C$, a value similar to $0{,}10°C$ found in the Peruvian Andes (Seiler et al., 2013) and less than $0{,}25°C$ found in Ecuador (Morán-Tejeda et al., 2016). Regarding precipitation, no clear trend was found. In a study of climate trends in Ecuador,Morán-Tejeda et al. (2016) did not find a significant trend in annual precipitation in the inter-Andean region. Wet periods such as 1965-1966, 1983-1984, 1993-1994, 1997-1998 and 2008 coincide with the standardized precipitation evapotranspiration index found by Vicente-Serrano et al. (2017) in the interandean region. A clear increase in precipitation in the period 1983-1984 coincides with the extreme El Niño phenomenon in that period. However, there is no significant increase in the other extreme period of El Niño (1997-1998). This behavior coincides with the study of dry and humid extremes in the city of Quito by Domínguez-Castro et al. (2018). Dry years such as 1961-62, 1967, 1979, 1986, 1991, 2003 and 2009 coincide with the results of Vicente-Serrano et al. (2017) and Domínguez-Castro et al. (2018).

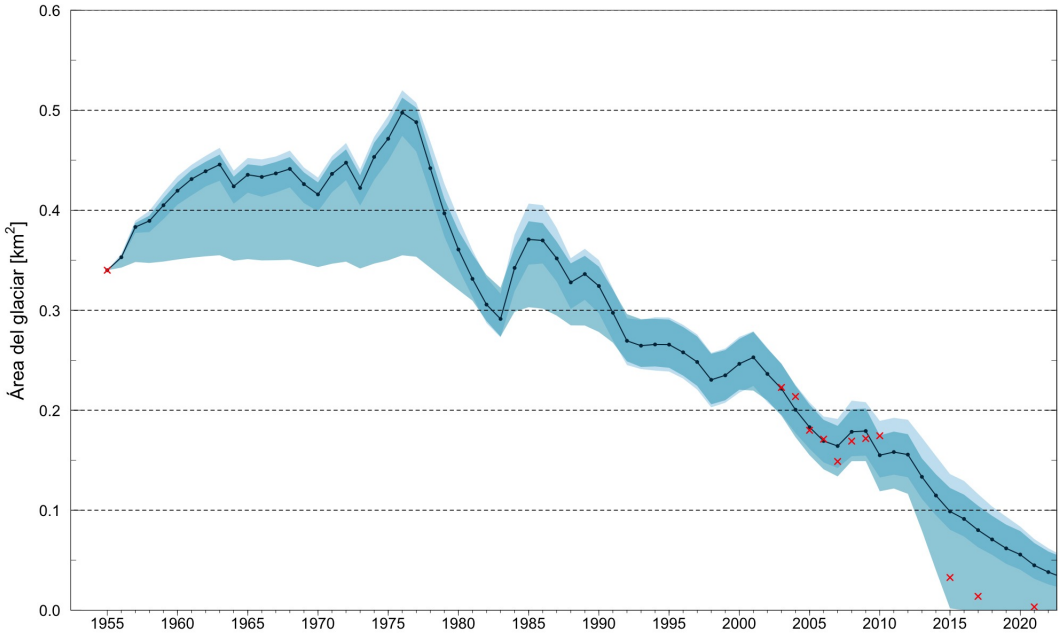

Figure 6. Variation Simulation of the Carihuairazo Glacier area (1956-2022) as a product of the hydroglaciological model. The red crosses correspond to the observed measurements of aerial photos (the first measurement in 1956 is represented in the model as the final value in 1955). The dotted dark solid line represents the model simulation with the calibrated reanalysis series. The light blue surface represents 95% of the 10000 simulations performed with the variation of the input variables using the calibrated parameters. The dark blue surface represents 95% of the 10000 simulations performed with the calibrated reanalysis input variables and the different parameter sets calibrated for the input variable variation. The darker blue band represents the intersection of the bands described above.

The parameters calibrated from observations of the glacier area are within typical values as evidenced in the literature (Table 1). The parameters relating the area and volume of the glacier ($a = 0{,}014$ and $b = 1{,}35$) are similar to those recommended for the study of the area-volume relationship of several glaciers of Bahr and Peckham (1997), where values of a=0.048 and b=1.36 are recommended. The parameter values obtained from the optimization of 10000 runs for different variations in the input variables reveal a large dispersion (Table 1). Bahr et al. (2015) performed a review of the area-volume relationship of glaciers for parameters a and b, and indicates that while parameter a can vary from glacier to glacier and can even change over time, the parameter should be fixed and its value should be between 1,167 and 1.5, otherwise it could cause inconsistencies in the mechanical equilibrium equations in glaciers. Grinsted (2013) also finds the value of b within this range. However, Radić et al. (2007), in a study of the evolution of 37 synthetic glaciers, found b values of 1.56 for stationary conditions, and even higher values (up to 2.90) for non-stationary conditions, concluding that parameter b is higher in warming scenarios (loss of glacial mass) and that it tends to increase with a smaller initial glacial size. This finding is in agreement with an evolution study of the small Chacaltaya glacier in Bolivia (Ramirez et al., 2001), where parameter b can be estimated from 2.05 in the period 1860-1998 from annual topographic measurements and geophysical studies carried out on the glacier. In this study, in 39% of cases parameter b is within the range recommended by Bahr et al. (2015). In 98% of cases, b is below 2.05. For the melting constants in the high and low ablation zone, the calibrated values are close to the values recommended by Fernández Yánez (2010), of 180 and 240 mm/month/$^{\circ}C$, respectively. However, the values found are lower than the range of 284 to 434 mm/month/$^{\circ}C$ used by Caro et al. (2023) in a simulation of glacier mass loss in the tropical Andean zone.

The development of the model allowed estima-

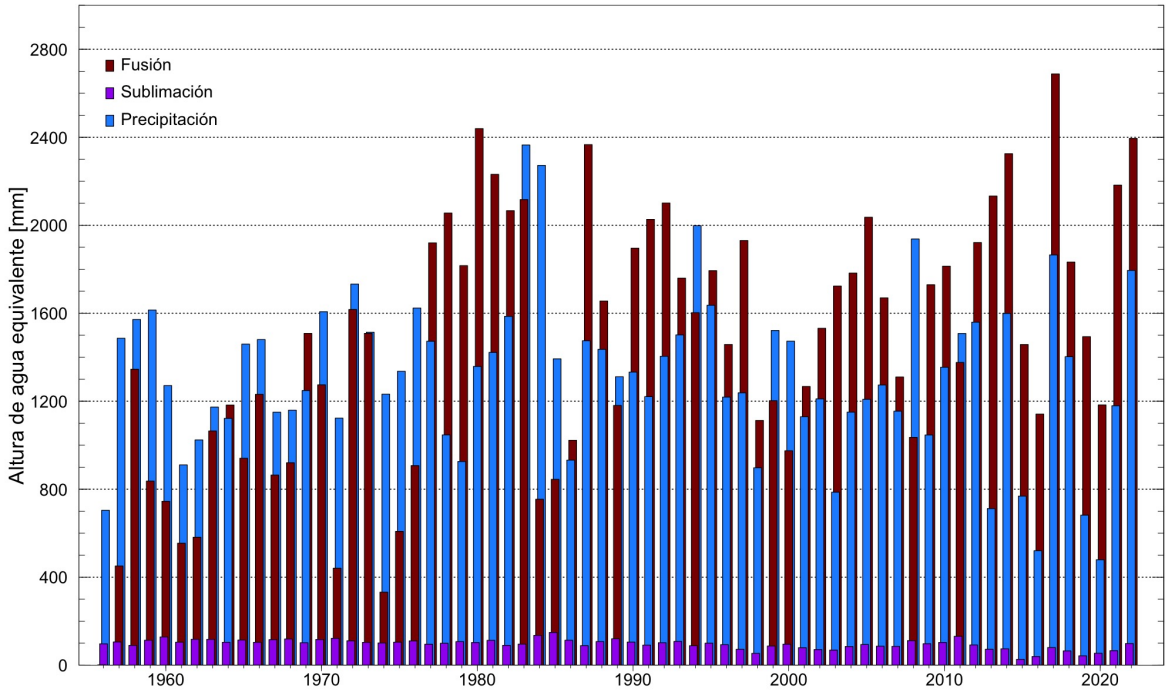

Figure 7. Annual mass balance in the Carihuairazo Glacier (1956-2022). The bars represent the variables of entry (precipitation) and exit (fusion and sublimation) that influence the mass balance of the glacier.

ting the variation in the volume of the glacier in a period of 68 years. The model shows an increase in the mass of the glacier until 1975 and later a constant loss of its mass, except for a few years (e.g. 1999-2000 and 2007-2008) where there is a slight recovery as a result of an excess in precipitation inputs or by the decrease in losses by sublimation and fusion, the last reduced by the reduction of temperature in those years. This accelerated loss of glacier volume since the late 1970s has been evident in the Andean glaciers of the tropical zone (Rabatel et al., 2013). Also, a worldwide significant decrease in the volume of glaciers has been reported since the beginning of the 21st century that coincides with the increase in sea level (Hugonnet et al., 2021). In Ecuador, a recession study of the Cotopaxi volcano glacier (Jordan et al., 2005) showed a similar behavior to that found in this study, where in the period 1956-1976 the Cotopaxi glacier maintained its mass, and subsequently suffered a 30 % retreat of its mass until 1997. In another study in the glacier of the volcano Antisana (Basantes-Serrano et al., 2022), a similar behavior can be evidenced except for the period 1956-1964, where there was a significant retreat of the glacier, and the period from 2000, where although the glacier had losses of mass, the retreat was not as significant as the period in the late 70's until 2000. This behavior differs from the retreat of the Carihuairazo glacier, where mass loss is similar between the 80s and the end of 2010. For the case of the Chimborazo volcano glacier, the closest to Carihuairazo, the loss of the glacier area between 1962 and 1997 was 57 % (Caceres, 2010), which is similar to the 48 % found in this study.

Although the model manages to successfully simulate the glacier area until 2010, it cannot reproduce the abrupt decline that occurs from 2011. Looking at the precipitation and temperature in this period, the temperature undergoes a considerable increase in 2011 to 2016, and subsequently a slight decrease (Figure 2). This variation in temperature is reflected in the decrease of the glacial area, but the loss of mass is not sufficient as seen in the observations. One factor that could explain the difference is the relationship between the volume and the area of the glacier. The model uses a constant ratio regardless of the size of the glacier. But this relationship can change especially when the area is reduced, since the influence of the topography of the mountain

will be more prevalent (for example the presence of bumps or depressions). This phenomenon could be explained by the edge effect that Santos and Tellería (2006) define as "the set of processes associated with the increase of the perimeter/area relationship that occurs with the advance of fragmentation". Also, it should be considered that the reduction of the glacier mass to such a small size (less than 0.1 km^2) can produce a change in the microclimate around the glacier, producing an increase in temperature that has not been evident. For example, the small Chacaltaya glacier in Bolivia, which had an area of 0.25 km^2 at the beginning of the 1940s, has suffered a retreat to extinction. By the beginning of the 21st century, the retreat meant an outlet from the heat supply for the melting of the glacier of 10 W/m^2 (Ramirez et al., 2001), equivalent to an increase of 1,5°C.

Another factor that could be considered in the simulation of the retreat of the Carihuairazo glacier is the influence of the eruptive process of the Tungurahua volcano. Vasconez et al. (2021) determined that in November 2015, 1.83E+06 m^3 of ash were released into the atmosphere. According to this same study the average wind direction during the eruption was towards the west, northwest and southwest. This research determined that the accumulated volcanic ash reached <100 g/m^2 in the highlands of the eastern flank of Chimborazo volcano. Due to the proximity of Carihuairazo to Tungurahua volcano, the ash emanations of the volcano were deposited in the glacier, partially covering the surface of ice and snow, causing a reduction in albedo. As a result, the ability to reflect shortwave radiation to the glacier may have been diminished, favoring melting and the subsequent glacier retreat dynamics. The accumulation of ash on the glacial surface of Chimborazo and Carihuairazo from the eruptions of Tungurahua exacerbated the deglaciation process, as Cruz points out (2020, personal interview): "A high albedo will reflect up to 90% of the light energy, on the contrary, the Tungurahua ash reduced the albedo in the glaciers of Chimborazo and Carihuairazo, so that up to 80% of the light energy was absorbed by the glacier, causing the formation of large penitent fields".

La Frenierre and Mark (2017) points out that the decrease in albedo exacerbates the effect of glacial surface warming, as observed in Kilimanjaro, in West Africa, where glacial retreat has been more sensitive to the decrease in albedo, due to reduced snowfall, than to increased temperatures.

The simulation of the model, the observations of the glacier area and the record of the volcanic activity of Tungurahua have been elaborated (Figure 8) with the information collected in the meteorological stations, which relates for each year the behavior of each of these variables in order to establish a possible connection between them and the glacial retreat of Carihuairazo. In the period 2003 to 2017, it can be observed that the variation in the glacier area is mainly related to the temperature variation in both the model results and the observations. On the contrary, precipitation shows an inverse relationship in several years. Regarding the activity of the Tungurahua volcano, an attempt has been made to characterize its activity in a qualitative way. There is no obvious relationship between activity and glacial area variation, but activity may explain some differences between the model and observations.

For the period 200- 2009, despite the favorable climatic conditions for a possible considerable recovery of the glacier, the coincidence of this period with one of the most violent eruptive phases of the Tungurahua volcano, we verify only a small recovery of the Carihuairazo glacier. For the period 2010-2015, there is no significant increase in the activity of the volcano that could explain the abrupt reduction in the glacier area. In this sense, the significant retreat in the area would be more related to the edge effect in the upper part of the glacier.

3.3.2 Impacts on socioeconomic, environmental and cultural systems

An attempt has been made to characterize the impact of the glacier retreat on the Cunucyacu community. Both the community members and the climbers interviewed agree on the dramatic glacial retreat in the Carihuairazo, their concerns and motivations may be different, but they refer to the same origin of the problem, the loss of the ice mass leaves a cultural trauma in their perception of this environment. More perils on the ascent routes, less water availability, and uncertainty about a glacier-free future in the Andes. The wasteland areas are the ones that ensure the provision of water for populations at

lower elevations. According to the research carried out by Buytaert et al. (2017), it was determined that the glacial contribution from Carihuairazo to the flows of the area is not representative, since it is below 4%. Although the retreat of Andean glaciers in Ecuador does not necessarily imply a decrease in water availability by itself, it is a clear indicator of the changes in conditions and temperatures of this ecosystem, and it also reveals a number of vulnerabilities associated with climate change, such as forced migration in search of better fields of cultivation, search for new water sources, better pastures, etc.

For Ana Segovia (2021, personal interview), the loss of the link with nature, specifically in the community of Cunucyacu, is due to the precarious living conditions that these people face. The lack of quality education, the distances that children have to travel to reach the community school, for example, makes that people who can afford send their children to study elsewhere, generating the conditions of future migration. One consequence of this phenomenon is that currently agriculture and livestock are managed by older adults. Segovia believes that it is also a problem of self-esteem, because it is considered that having some kind of binding belief with the mountains is wrong, not properly valued. In addition, the general perception that associates life in these areas with poverty and marginalization is very present. This uprooting of communities in front of the paramo has its interpretation in the change of land tenure, which for Luis Chicaiza (2021, personal interview) is a structural problem, since many communities were displaced from low, more productive areas, to high land, less productive for agriculture, forcing them to change land use in their search for resources for their subsistence.

As for Susana Escandón (2021, personal interview), water is one of the elements around which conflicts, knowledge, economic dynamics, etc. occur, so it is important to consider this multidimensionality of water when making comprehensive decisions about it. In this sense, it explains another way of understanding this process of disconnection, due to the decrease of resources in these territories, and which now no longer turn out to be as visible or powerful as before.

Based on the interview with Mr. Luis Punina, a local community guide, the main concern they have about the glacial retreat of Carihuairazo is the consequences in the tourist area, above even the possible implications in the availability of water for the community. Since they have the idea that visits to the sector are only due to the interest of approaching the snowy mountain, and once the glacier has disappeared, they have noticed a decrease in tourists. It is important to consider that this study has coincided temporarily with the confinement measures decreed in the context of COVID-19. At the meeting held with the community assembly on September 11, 2020, the members expressed their confidence that since the time of their grandparents, they have not lacked water, and they are confident that they will not be lacking in the future, regardless of whether the Carihuairazo glacier will disappear completely. So they show a complete disinterest in generating plans and actions that allow them to adapt to possible threats. Despite this, they have already begun to look for new sources of water supply from the Chimborazo glaciers.

Great respect for nature was one of the values rooted in the worldview of the high Andean indigenous communities, but the new generations today have a new way of understanding their environment as Mesías Usigña (2021, personal interview) points out. Factors such as religion, dispossession of arable land, migration, changes in the ways of consumption of communities and especially cities have generated inadequate living conditions around the mountains, the search for more resources has made people separate from their symbols and beliefs.

The choice we face as a society shows on the one hand the demand of care of the wasteland towards the communities for all people who benefit from it, and on the other hand is the legitimate remuneration that cities owe to communities for their conservation actions of the wasteland. It is necessary to establish the link between the urban and the rural, understand the origin of the water coming to our cities, since it will help to make visible the need for fair treatment with the communities that are responsible for the protection of the moors. It is important to value family peasant production systems, which are those that provide the cities.

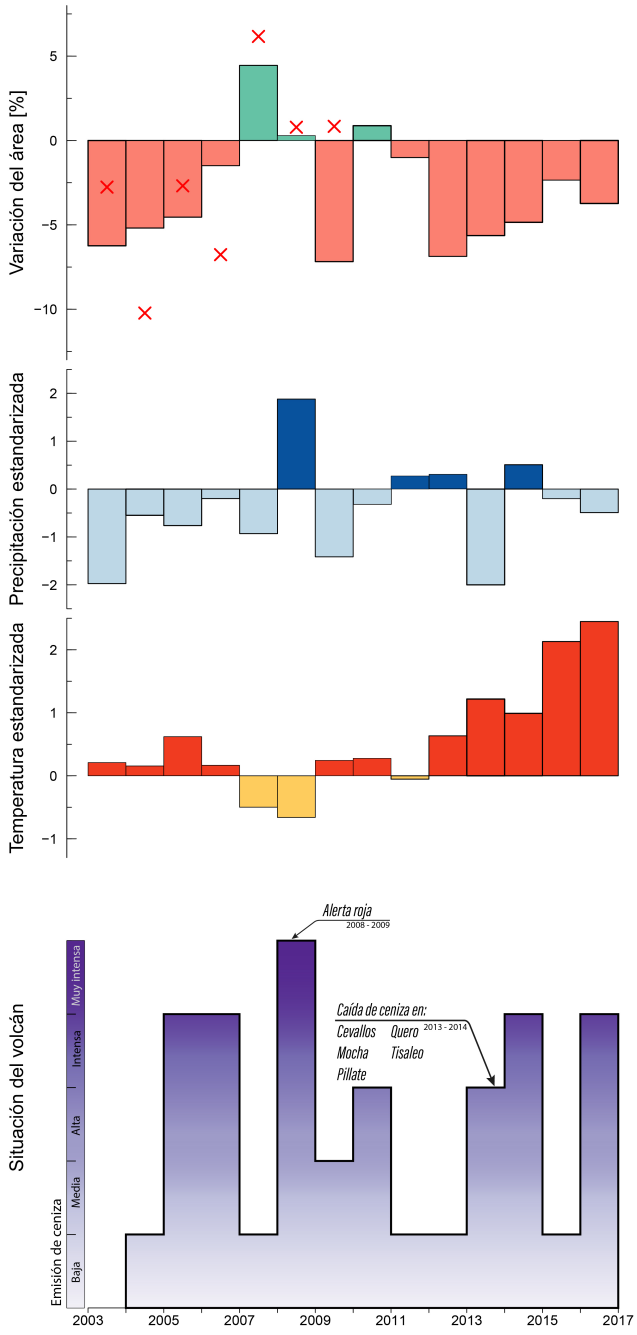

Figure 8. Relationship between the variation of the surface of the Carihuairazo glacier, precipitation, temperature and volcanic activity of Tungurahua between 2003 and 2017. The first graph shows the increase or loss of the area between each year in relation to the year 1956 (0.34 km^2), the bars correspond to the simulation of the hydroglaciological model and the red crosses to the measurements of the glacier contour (only years followed by observations were included). In the second graph, standardized precipitation is observed for each year. The third figure shows the standardized temperature in each year. The fourth graph shows the characterization of the volcanic activity of Tungurahua in relation to ash emission and point events.

Water should be considered "as a dynamizer of the peasant community organization" (Chicaiza 2021, personal interview). This perception of water as something more than just a resource, would facilitate the commitment of conservation of the sources from cities, towns and communities. Tensions around the paramo reveal deeper issues of inequality and marginalization that motivate migration processes in several aspects: land tenure, access to quality education, access to basic services, access to water of the same quality as that reaching the big cities, etc. Attempts to slow the advance of the agricultural frontier, care for water that others use, are some of the many faces of this crisis. In the last ten years, we have been able to generate data and models on the possible climate scenarios that our region could face; however, this information has not reached farmers and less so the communities that inhabit the moors, so part of this awareness process of climate change must be crossed by the democratization of climate information, which allows them to understand and adapt to the changes that are evident and that sooner or later will affect their ways of life.

Although currently indigenous communities do not specifically discuss climate change, it does not mean that they are oblivious to this reality, since for them a substantial change in their agricultural calendar is noticeable. Perhaps their discussions are more focused on issues that are considered priorities for their daily subsistence, and they will not be able to properly articulate a climate change agenda as long as their most basic needs are not met.

3.3.3 Adaptation needs, challenges and opportunities

The socio-economic context of Cunucyacu is complex, since out of its 12,218 inhabitants, 95% of the population live under poverty conditions, in an environment where not everyone has access to basic services, and do not reach to cover the basic family basket (GAD Parroquía Rural de Pilahuín, 2015). Irrigation to support crops that are not normally irrigated could become more important in the coming years due to rainfall variability. Therefore, irrigation infrastructure should enable this type of assistance, through mobile spraying or drip irrigation systems, and thus ensure food security for this population (Gobierno Provincial de Tungurahua, 2011).

We still do not fully understand the importance of glaciers in hydrological cycles, and despite this we do not have a network for monitoring and surveillance of glacial behavior in the Andes, causing serious uncertainties in the attempts to model the behavior of these ice masses and their future influence on the water supply for our fields and cities.

3.3.4 Limitations of the research

Regarding the implementation and validation of the hydroglaciological model, one of the limitations was the available measurements. There are no stations on the glacier and the nearby weather stations are rare. In addition, it is necessary to consider the uncertainty of the reconstruction of the series from the use of the ERA5 reanalysis. For this reason, there is uncertainty in the time series of the input meteorological variables used in the model that reaches an error in the estimates of the area of the glacier of 0.02 km^2. However, the main limitation is the limited number of measurements that serve to validate the model, which in this case are the measurements of the glacier area. Unfortunately, between 1957 and 2000, there is no data for the glacier area. The limited number of measurements of the glacier area generates uncertainty in the values of the calibrated parameters of the model since there may be the problem of equifinality, because there are not enough restrictions to include the uncertainty of the meteorological variables of entry. In this sense, the average error in the estimations of the area reaches 0.05 km^2 and is greater in the decades where there are no observations. However, the model manages to simulate the glacier retreat satisfactorily.

Regarding the perception of the community regarding the retreat of the glacier, the greatest limitation faced by this research was the restrictions of the COVID-19 pandemic that coincided with the time of field work. Another limitation was the community's refusal to conduct perception surveys after meetings and agreements with the community's leadership. Therefore, it was not possible to have a statistical input, to contrast with other preservation experiences of the paramo; interviews were conducted with different actors working in research tasks, water funds, leadership of indigenous organizations, private reserves and international agencies,

to obtain a broader view of the socio-environmental situation of the paramos in Ecuador.

4 Conclusions

From a photographic record, community testimonies and measurements of the contour of the Carihuairazo glacier, it is concluded that the Carihuarizado glacier has experienced a significant retreat. Relative to the year 1956, the glacier has lost 97.1% and 99.1% of its surface area by 2017 and 2021, respectively. The use of a hydroglaciological model evidences the loss of the glacial area from the late 70s, except for a few years where a slight recovery is evident. The decline coincides with the positive trend in temperature increase over the years, this variable being the one that would have the greatest influence on the reduction of glacier volume. The model used has some limitations and cannot incorporate external factors such as ash fall from the Tungurahua volcano.

The climatic and altitude conditions to which this small mass of ice is subjected place it in a situation of inevitable extinction. Although the retreat of Andean glaciers in Ecuador does not necessarily imply a decrease in water availability by itself, because it is mainly the moors that ensure the provision of water for populations, it is a clear indicator of the changes in conditions and temperatures faced by this ecosystem.

It is necessary to persist on the need to collect meteorological information in the areas near the glaciers of the Ecuadorian Andes and to adjust models that allow predicting their behavior in the coming years to constitute a scientific basis that facilitates proposing adaptation measures.

The glacial retreat will affect some areas such as the landscape and with it there could be an impact on local tourism, but its impact on water supply will be limited, however an articulated conservation process moor - glacier, considering it as complementary elements, would allow better management of policies and actions to implement.

Finally, the scientific community must maintain links with the communities that are affected by this glacial retreat, since finally it is the people who make this reality evident beyond the behavior of the weather series.

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References

Aguilar-Lome, J., Espinoza, R., Espinoza, J., Rojas-Acuña, J., Willems, B., and Leyva, W. (2019). Elevation-dependent warming of land surface temperatures in the andes assessed using modis lst time series (2000-2017). *International Journal of Applied Earth Observation and Geoinformation*, 77:119–128. Online:https://n9.cl/wjgde.

Bahr, D., Pfeffer, W., and Kaser, G. (2015). A review of volume-area scaling of glaciers. *Reviews of Geophysics*, 53(1):95–140. Online:https://n9.cl/dfiof.

Bahr, D.and Meier, M. and Peckham, S. (1997). The physical basis of glacier volume-area scaling. *Journal of Geophysical Research: Solid*

Earth, 102(B9):20355–20362. Online:https://n9.cl/8u4xq.

Basantes, R. (2010). Análisis espacio-temporal de comportamiento geométrico de los glaciares del volcán antisana y su relación con la variabilidad climática. Master's thesis, Univ. Nice, France.

Basantes-Serrano, R., Rabatel, A., Francou, B., Vincent, C., Maisincho, L., Caceres, B., Galarraga, R., and Alvarez, D. (2016). Slight mass loss revealed by reanalyzing glacier mass-balance observations on glaciar antisana 15α (inner tropics) during the 1995–2012 period. *Journal of Glaciology*, 62(231):124–136. Online:https://n9.cl/ir0ws.

Basantes-Serrano, R., Rabatel, A., Francou, B., Vincent, C., Soruco, A., Condom, T., and Ruíz, J. (2022). New insights into the decadal variability in glacier volume of a tropical ice cap, antisana (0° 29 s, 78° 09 w), explained by the morphotopographic and climatic context. *The Cryosphere*, 16(11):4659–4677. Online:https://n9.cl/2k8ja.

Bradley, R., Keimig, F., Diaz, H., and Hardy, D. (2009). Recent changes in freezing level heights in the tropics with implications for the deglacierization of high mountain regions. *Geophysical Research Letters*, 36. Online:https://n9.cl/0xqs2w(17).

Buytaert, W., Moulds, S., Acosta, L., De Bièvre, B., Olmos, C., Villacis, M., Tovar, C., and Verbist, K. (2017). Glacial melt content of water use in the tropical andes. *Environmental Research Letters*, 12(11):114014. Online:https://n9.cl/afbv7.

Byrd, R., Lu, P., Nocedal, J., and Zhu, C. (1995). A limited memory algorithm for bound constrained optimization. *SIAM Journal on scientific computing*, 16(5):1190–1208. Online:https://n9.cl/1p00f.

Cabrera, A. and Romero, H. (2013). Evaluación cualitativa de la vulnerabilidad al cambio climático de los principales ecosistemas del distrito metropolitano de quito. vulnerabilidad de ecosistemas: evaluación cualitativa (wp5).

Caceres, B. (2010). Actualización del inventario de tres casquetes glaciares del ecuador. Master's thesis, Université Nice Sophia Antipolis.

Cáceres, B. and Cauvy, S. (2015). Carihuayrazo sw a little ecuadorian glacier in the way to extinction. In *AGU Fall Meeting*, number C13B-0812, pages 58–77.

Cáceres, B., Francou, B., Bontron, G., Tachker, P., Bucher, R., and Villacis, M. (2006). El glaciar 15 del antisana: investigaciones glaciológicas y su relación con el recurso hídrico. In *(Proceedings of the Fifth FRIEND World Conferenceheld at Havana*, volume 308, pages 479–482. Online:https://n9.cl/agivop.

Caro, A., Condom, T., Rabatel, A., Champollion, N., García, N., and Saavedra, F. (2023). Hydrological response of andean catchments to recent glacier mass loss. *EGUsphere*, 2023:1–26.

CECS (2009). Estrategia nacional de glaciares. fundamentos. techreport, Centro de Estudios Científicos.

Clapperton, C. (1990). Glacial and volcanic geomorphology of the chimborazo-carihuairazo massif, ecuadorian andes. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 81(2):91–116. Online:https://n9.cl/8gwljz.

Condom, T., Escobar, M., Purkey, D., Pouget, J., Suarez, W., Ramos, C., Apaestegui, J., Zapata, M., Gomez, J., and Vergara, W. (2011). Modelling the hydrologic role of glaciers within a water evaluation and planning system (weap): a case study in the rio santa watershed (peru). *Hydrology and Earth System Sciences Discussions*, 8(1):869–916. Online:https://n9.cl/zna9h.

Domínguez, C., Villacs, M., Pouget, J., Condom, T., Maisincho, L., and R., G. (2012). Modelación hidroglaciológica con escenarios globales a2 y b2 en el glaciar crespos del antisana. Technical report. Documento no publicado.

Domínguez-Castro, F., García, R., and Vicente, S. (2018). Wet and dry extremes in quito (ecuador) since the 17th century. *International Journal of Climatology*, 38(4):2006–2014. Online:https://n9.cl/vl418.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P., and Ruiz, L. (2019). Two decades of glacier mass loss along the andes. *Nature Geoscience*, 12(10):802–808. Online:https://n9.cl/r1m8c.

El Comercio (2009). Cronología de la erupción del volcán tungurahua en los últimos 10 años. El Comercio. Online:https://n9.cl/czgyl.

El Comercio (2016). Volcán tungurahua arroja ceniza por segundo día y afecta los cultivos. El Comercio. Online:https://n9.cl/v19e2w.

Favier, V., Coudrain, A., Cadier, E., Francou, B., Ayabaca, E., Maisincho, L., Praderio, E., Villacis, M., and Wagnon, P. (2008). Evidence of groundwater flow on antizana ice-covered volcano, ecuador/mise en évidence d'écoulements souterrains sur le volcan englacé antizana, equateur. *Hydrological Sciences Journal*, 53(1):278–291. Online:https://n9.cl/zg14u.

Favier, V., Wagnon, P., Chazarin, J., Maisincho, L., and Coudrain, A. (2004). One-year measurements of surface heat budget on the ablation zone of antizana glacier 15, ecuadorian andes. *Journal of Geophysical Research: Atmospheres*, 109. Online:https://n9.cl/jwekz(D18).

Fernádez, A. (2018). Aplicación de balance de energía para analizar el forzamiento atmosférico en la producción de caudales en un glaciar tropical. caso de estudio: Glaciar 12 del volcán antisana. Master's thesis, Escuela Politécnica Nacional.

Fernández Yánez, A. O. (2010). Modelación del balance de masa del galciar 15a del volcán antisana usando software weap. resreport, Escuela Politécnica Nacional, Quito.

Francou, B., Cáceres, B., Villacís, M., Basantes, R., Maisincho, L., Galárraga, R., and Romero, C. (2011). *Analizando el cambio climático a partir de los glaciares del Ecuador*. IRD, SENECYT, EPMAPS, INAMHI, EPN.

Francou, B., Vuille, M., Favier, V., and Cáceres, B. (2004). New evidences of enso impacts on glaciers at low latitude: Antizana 15, andes of ecuador, 0 28'. *Journal of Geophysical Research*, 109. Online:https://n9.cl/zxwgq:1029.

French, A. adn Baraer, M., Bury, J., Carey, M., Mark, B., McKenzie, J., and Polk, M. (2016). *Naturaleza y sociedad: Perspectivas socio-ecológicas sobre cambios globales en América Latina*, chapter Coyuntura crítica: cambio climático, globalización y doble exposición en el sistema socio-hidrológico de la cuenca del río Santa, Perú, pages 303–340. IEP and INTE-PUCP.

GAD Parroquía Rural de Pilahuín (2015). Plan de desarrollo y ordenamiento territorial 2015-2020. techreport, Gobierno Autónomo Desentralizado de Pilahuín.

García, R. (2022). La variabilidad climática en la cuenca hidrográfica del río chalpi grande y su importancia para los sistemas de abastecimiento de agua potable para la ciudad de quito.

Gobierno Provincial de Tungurahua (2011). Programa de agua y cuencas del tungurahua. informe principal. techreport, Gobierno Provincial de Tungurahua y Consorcio kfw-CES-GFA.

Grinsted, A. (2013). An estimate of global glacier volume. *The Cryosphere*, 7(1):141–151. Online:https://n9.cl/gh46r.

Gualco, L., Maisincho, L., Villacís, M., Campozano, L., Favier, V., Ruiz, J., and Condom, T. (2022). Assessing the contribution of glacier melt to discharge in the tropics: the case of study of the antisana glacier 12 in ecuador. *Frontiers in Earth Science*, 10:732635. Online:https://n9.cl/djm22.

Guijarrom, J. (2023). Climatol: Climate tools (series homogenization and derived products). Cran.r-project. Online:https://n9.cl/zf30y.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N. (2020). The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730):1999–2049.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., and Brun, F. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, 592(7856):726–731. Online:https://n9.cl/6ff11u.

Imfeld, N., Sedlmeier, K., Gubler, S., Correa, K., Davila, C., Huerta, A., Lavado, W., Rohrer, M., Scherrer, S., and Schwierz, C. (2021). A combined

view on precipitation and temperature climatology and trends in the southern andes of peru. *International journal of climatology*, 41(1):679–698. Online:https://n9.cl/twlia.

Instituto Geofísico de la Politécnica Nacional (2015). Informe especial del volcán tungurahua n°. 10. Instituto Geofísico de la Politécnica Nacional. Online:https://n9.cl/zf30y.

Intergovernmental Panel on Climate Change (IPCC) (2022). Contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change. In *Climate Change 2022: Impacts, Adaptation, and Vulnerability*.

Johansen, K., Alfthan, B., Baker, E., Hesping, M., Schoolmeester, T., and Verbist, K. (2019). *El Atlas de Glaciares y Aguas Andinos: el impacto del retroceso de los glaciares sobre los recursos hídricos*. UNESCO Publishing.

Jordan, E., Ungerechts, L., Cáceres, B., Penafiel, A., and Francou, B. (2005). Estimation by photogrammetry of the glacier recession on the cotopaxi volcano (ecuador) between 1956 and 1997/estimation par photogrammétrie de la récession glaciaire sur le volcan cotopaxi (equateur) entre 1956 et 1997. *Hydrological Sciences Journal*, 50(6):961. Online:https://n9.cl/37pa4.

Juen, I. (2006). *Glacier mass balance and runoff in the tropical Cordillera Blanca, Perú.* PhD thesis, University of Innsbruck.

Kalnay, E., Kanamitsu, M., Kistler, R.and Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., and Woollen, J. (1996). The ncep/ncar 40-year reanalysis project. *Bull. Am. Meteor. Soc*, 77:437–471. Online:https://n9.cl/ckmfm.

La Frenierre, J. and Mark, B. (2017). Detecting patterns of climate change at volcán chimborazo, ecuador, by integrating instrumental data, public observations, and glacier change analysis. *Annals of the American Association of Geographers*, 107(4):979–997.

Manciati, C., Villacís, M., Taupin, J., Cadier, E., Galárraga-Sánchez, R., and Cáceres, B. (2014). Empirical mass balance modelling of south american tropical glaciers: case study of antisana volcano, ecuador. *Hydrological Sciences Journal*, 59(8):1519–1535.

Morán-Tejeda, E., Bazo, J., López, J., Aguilar, E., Azorín-Molina, C., Sanchez-Lorenzo, A., Martínez, R., Nieto, J., Mejía, R., and Martín, N. (2016). Climate trends and variability in ecuador (1966–2011). *International Journal of Climatology*, 36(11):3839–3855. Online:https://n9.cl/7553z.

Moreno, R. (2023). Restauración geomorfológica sobre depósitos de relaves: caso de estudio aplicado a la concesión minera río blanco, ecuador. *La Granja*, 37(1):130–141. Online:https://n9.cl/7553z.

Naranjo-Silva, S. (2024). A hydropower development perspective in ecuador: past, present, and future. *La Granja*, 39. Online:https://n9.cl/tea6hr(1).

Pacheco-Peña, D., Quinga, L. L., and Moretta, P. Y. (2023). Cogestión del agua entre actores públicos y comunitarios como herramienta de adaptación al cambio climático global: el caso de la comuna santa clara de san millán, dm quito. *La Granja*, 37(1):44–57. Online:https://n9.cl/aecgrj.

Piedra Santillan, D. (2021). Modelación hidro glaciológica con escenarios globales rcp8. 5 y rcp4. 5 en el glaciar crespos del antisana. Master's thesis, Escuela Politécnica Nacional.

Postigo, J. (2013). *Cambio climático, movimientos sociales y políticas públicas. Una vinculación necesaria*, chapter Desencuentros y (potenciales) sinergias entre las respuestas de campesinos y autoridades regionales frente al cambio climático en el sur andino peruano, pages 181–216. CLACSO.

Pouget, J. (2011). Propuesta del modelo ice kiss como un componente de un sistema de apoyo a la planifcación de los recursos hídricos. resreport, IRD, Quito.

Pouget, J., Proaño, D., Vera, A., Villacís, M., Condom, T., Escobar, M., Le Goulven, P., and Calvez, R. (2017). Modélisation glacio-hydrologique et gestion des ressources en eau dans les andes équatoriennes: L'exemple de quito. *Hydrological Sciences Journal*, 62(3):431–446. Online:https://n9.cl/vhyjw.

Pouyaud, B., Francou, B., and Ribstein, P. (1995). Un réseau d'observation des glaciers dans les andes tropicales. *Bulletin de l'Institut Français d'Etudes Andines*, 24(3):707–714. Online:https://n9.cl/na5s1.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J., Basantes, R., Vuille, M., Sicart, J., and Huggel, C. (2013). Current state of glaciers in the tropical andes: a multi-century perspective on glacier evolution and climate change. *The Cryosphere*, 7(1):81–102. Online:https://n9.cl/4wqs6n.

Radić, V., Hock, R., and Oerlemans, J. (2007). Volume-area scaling vs flowline modelling in glacier volume projections. *Annals of Glaciology*, 46:234–240. Online:https://n9.cl/4rhg6.

Ramírez, E. (2008). Impactos del cambio climático y gestión del agua sobre la disponibilidad de recursos hídricos para las ciudades de la paz y el alto. *Revista Virtual LEDESMA*, 2(3):49–61. Online:https://n9.cl/fmpyf.

Ramirez, E., Francou, B., Ribstein, P., Descloitres, M., Guerin, R., Mendoza, J., Gallaire, R., Pouyaud, B., and Jordan, E. (2001). Small glaciers disappearing in the tropical andes: a case-study in bolivia: Glaciar chacaltaya (16o s). *Journal of Glaciology*, 47(157):187–194. Online:https://n9.cl/j9mb5.

Rhoades, R. (2008). Desaparición del glaciar mama cotacachi: investigación etnoecológica y cambio climático en los andes de ecuador. *Pirineos*, 163:37–50. Online:https://n9.cl/z4dga.

Rosero, P., Crespo, V., Espinosa, R., Andino, P., Barragán, Á., Moret, P., Gobbi, M., Ficetola, G., Jaramillo, R., Muriel, P., et al. (2021). Multi-taxa colonisation along the foreland of a vanishing equatorial glacier. *Ecography*, 44(7):1010–1021. Online:https://n9.cl/sh10d.

Salcedo, S. (2019). Variación espaciotemporal de impurezas (partículas) absorbentes de luz y cenizas volcínicas en la superficie del nevado coropuna, arequipa. Master's thesis, Universidad Nacional de San Agustín de Arequipa.

Sandoval, C. (2021). Sistemas inteligentes para la protección de ecosistemas, flora y fauna. *UNIVERSIDAD, CIENCIA y TECNOLOGÍA*, 25(110):138–154. Online:https://n9.cl/54lbv.

Santos, T. and Tellería, J. (2006). Pérdida y fragmentación del hábitat: efecto sobre la conservación de las especies. *Ecosistemas*, 15(2):3–12. Online:https://n9.cl/uyz2w.

Seiler, C., Hutjes, R., and Kabat, P. (2013). Climate variability and trends in bolivia. *Journal of applied meteorology and climatology*, 52(1):130–146. Online:https://n9.cl/xs4ht1.

Sicart, J., Hock, R., and Six, D. (2008). Glacier melt, air temperature, and energy balance in different climates: The bolivian tropics, the french alps, and northern sweden. *Journal of Geophysical Research: Atmospheres*, 113. Online:https://n9.cl/c1bys(D24).

Vasconez, F., Maisincho, L., Andrade, S., Cáceres, B., Bernard, B., Argoti, C., Telenchana, E., Almeida, M., Almeida, S., and Lema, V. (2021). Secondary lahars triggered by periglacial melting at chimborazo volcano, ecuador. *Revista Politécnica*, 48(1):19–30. Online:https://n9.cl/c7n38.

Vicente-Serrano, S., Aguilar, E., Martínez, R., Martín, N., Azorin, C., Sánchez, A., El Kenawy, A., Tomás, M., Moran, E., and López, J. (2017). The complex influence of enso on droughts in ecuador. *Climate Dynamics*, 48:405–427. Online:https://n9.cl/6j2gz.

Vilela, M. (2011). *Cambio climático, movimientos sociales y políticas públicas. Una vinculación necesaria*, chapter Desencuentros y (potenciales) sinergias entre las respuestas de campesinos y autoridades regionales frente al cambio climático en el sur andino peruano, pages 181–216. CLACSO.

Villacis (2008). Ressources en eau glaciaire dans les andes d'equateur en relation avec les variations du climat: le cas du volcan antisana. Master's thesis, Université Montpellier II.

Vuille, M. (2013). El cambio climático y los recursos hídricos en los andes tropicales. *Banco Interamericano de Desarrollo*, 21. Online:https://n9.cl/qze2o.

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Landslides Susceptibility Analysis employing Analytical Hierarchy Process on an Amazonian roadway in Ecuador

Análisis de Susceptibilidad a Deslizamientos empleando el Proceso de Jerarquía Analítica en una carretera amazónica del Ecuador

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Abstract

The Puyo-Tena roadway is prone to landslides due to the geodynamics, geomorphology, and geological materials of the area (unstable outcrops and strata). In recent years, this problem has persistently caused the road to be partially or completely disabled on numerous occasions. The objective of the research was to generate a cartographic model of landslides susceptibility based on variables such as slope, geological formations, land cover and land use, as well as distances to faults, road, and rivers. The degree of landslides incidence was estimated as the linear combination of the weighted variables using the analytic hierarchy process. The importance of this semi-quantitative method lies in its ability to break down a complex decision problem into a simpler and more coherent decision model. The resulting cartographic model was classified into five susceptibility categories: very low, low, moderate, high, and very high. The results showed that 17 km out of the 80 km of the Puyo-Tena roadway have a high probability of landslides, which is equivalent to 21.25% of the road. Furthermore, within this percentage, it was determined that there are fifteen regions with a high probability of landslides due to their location in areas with steep slopes, porous and permeable lithology, a large number of rivers, and agricultural soils. The area under the curve (AUC) of the receiver operating characteristic (ROC) was used for model verification. The verification results showed that the cartographic model for the study area has an accuracy value of 83.7%. The cartographic model of landslide susceptibility will enable relevant decisions to be made to mitigate potential hazards that may endanger transporters, material goods, and residents of the area.

Keywords: susceptibility, landslide, analytical hierarchy process, geographic information system (GIS), susceptibility mapping model.

Resumen

La carretera Puyo-Tena es propensa a deslizamientos de tierra debido a la geodinámica, geomorfología y materiales geológicos de la zona (afloramientos y estratos inestables). En los últimos años, este problema ha provocado de forma persistente la inutilización parcial o total de la carretera en numerosas ocasiones. El objetivo de la investigación fue generar un modelo cartográfico de susceptibilidad a deslizamientos a partir de variables como la pendiente, las formaciones geológicas, la cobertura y uso de la tierra, así como las distancias a fallas, carretera y ríos. El grado de incidencia de deslizamientos se estimó como la combinación lineal de las variables ponderadas mediante el proceso de jerarquía analítica. La importancia de este método semicuantitativo radica en su capacidad para desagregar un problema de decisión complejo en un modelo de decisión más simple y coherente. El modelo cartográfico resultante se reclasificó en cinco categorías de susceptibilidad: muy baja, baja, moderada, alta y muy alta. Los resultados mostraron que 17 km de los 80 km de la carretera Puyo-Tena tienen una alta probabilidad a deslizamientos, lo que equivale a 21,25% de la carretera. Además, dentro de este porcentaje, se determinó que existen quince regiones con alta probabilidad de deslizamientos debido a su ubicación en zonas con fuertes pendientes, litología porosa y permeable, gran cantidad de ríos y suelos agrícolas. Para la verificación del modelo se utilizó el área bajo la curva (en inglés AUC) de la característica operativa del receptor (en inglés ROC). Los resultados de la verificación mostraron que el modelo cartográfico para el área de estudio tiene un valor de precisión de 83,7%. El modelo cartográfico de susceptibilidad a deslizamientos permitirá tomar las decisiones pertinentes para mitigar eventos potenciales que puedan poner en peligro a transportistas, bienes materiales y residentes de la zona.

Palabras clave: susceptibilidad, deslizamiento, proceso de jerarquía analítica, sistema de información geográfica (SIG), modelo cartográfico de susceptibilidad.

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1 Introduction

Landslides are characterized as mass movements of rocks, soil and debris down the slope under the direct influence of gravity (Cruden, 1991; Cruden and Varnes, 1996). These movements are part of the geological dynamics of the planet influenced by human activities, rains or static overloads, causing them to accelerate and in some cases be catastrophic (Pourghasemi et al., 2018; Basu and Pal, 2020). Landslide susceptibility indicates how likely a specific area is to fail, either locally or regionally (Hearn and Hart, 2019). This susceptibility is usually expressed with a landslide susceptibility mapping model showing the probability of landslide occurrence, regardless of the time scale. The relevance of these mapping models is that their development is specific and detailed about a particular area.

Mapping to determine landslide susceptibility analyzes variables that affect soil stability such as geology, geomorphology, topography and distance to rivers (Raghuvanshi et al., 2014; Dahal and Dahal, 2017; Hamza and Raghuvanshi, 2017; Vásquez, 2023). The development of susceptibility cartographic models considers data quality, spatial resolution of the work area and the methodology for the analysis and digitization of the variables used (Mansouri Daneshvar, 2014). The development of these models considers qualitative approaches (such as the heuristic method and the Mora-Charson-Mora method), quantitative approaches (such as the deterministic method and the statistical method) or the union of both. Historically, the first models to be developed consisted of qualitative data with geological and morphological aspects of landslides inventoried (Nilsen et al., 1979; Mallick et al., 2018). Progressively, they were further refined and included more robust analyzes such as analytical hierarchy analyzes (Komac, 2006; Tešić et al., 2020; Chanu and Bakimchandra, 2022), bivariate (Van Westen, 1997; Jamir et al., 2022), multivariate (Carrara, 1983; Benchelha et al., 2020; Pham et al., 2021), logistic regression(Dai et al., 2001; Lee and Min, 2001; Nhu et al., 2020; Wubalem and Meten, 2020), fuzzy logic (Ercanoglu and Gokceoglu, 2004; Bahrami et al., 2021; Bien et al., 2022) and artificial neural networks (Bragagnolo et al., 2020; Bravo-López et al., 2022; Gameiro et al., 2022).

Qualitative methods are characterized by incorporating expert opinion based on small-scale empirical results (Demir et al., 2013; Roccati et al., 2021; Asmare, 2023). In general, the most common qualitative methods are limited to analyzing the geological and geomorphological properties of landslides inventoried. However, there are more sophisticated qualitative methods such as semi-quantitative methods (Nicu and Asăndulesei, 2018; Dolui et al., 2019). A semi-quantitative method uses weighting and classification procedures in qualitative methods. A clear example is the analytical hierarchy process developed by Saaty (1990), which has been employed in this research. This method has become a widely used tool as it helps decision makers to choose the best criterion, reducing complex decisions to a series of comparative pairs and synthesizing the results (Sonker et al., 2021). Hence, this tool has been widely used by several researchers in the world for developing mapping models for landslide susceptibility (Guillen et al., 2022; Ozturk and Uzel-Gunini, 2022; Salcedo et al., 2022; Wang et al., 2022; Okoli et al., 2023).

A characteristic of the Amazon region of Ecuador is the frequency of landslides around major towns and major road networks (Gobierno Cantonal de Pastaza, 2020; Gobierno Provincial de Napo, 2020; Secretaría Técnica de la Circunscripción Territorial Especial Amazónica , 2021; Servicio Nacional de Gestión de Riesgos y Emergencias, 2022a,b). However, the low spatial resolution of the susceptibility models available at regional scale prevents to know the susceptibility of point areas (Zumpano et al., 2014). For example, the Puyo-Tena highway, located between the provinces of Pastaza and Napo, does not have detailed studies by the decentralized autonomous governments regarding the susceptibility to landslides as seen in the reports of the Gobierno Cantonal de Pastaza (2020) and the Gobierno Provincial de Napo (2020). This road often presents constant landslides that have affected the road between both provinces (Ecoamazónico, 2014, 2020, 2021; Correo, 2017; Obras Públicas Ecuador , 2022). Therefore, this research aims to generate a landslide susceptibility mapping model that identifies the regions most prone to landslides along the Puyo-Tena road. The route is considered an important network connecting Ecuador with its Amazon region.

2 Study Area

The research was carried out on the Puyo-Tena highway, between the provinces of Pastaza and Napo, in the Ecuadorian Amazon (Figure 1). The road is bounded to the west by the Cordillera Real, to the north by the canton Tena, to the east by the Basin Oriente and to the south by the province of Pastaza. In addition, it has a wide variety of landforms such as mountainous regions, slopes and plains (Ministerio del Ambiente de Ecuador, 2014).

The aspects that comprise the study area are slope (from 5° to >70°), altitude (from 449 meters above sea level (hereinafter m.a.s.l) to 1108 m.a.s.l), precipitation (from 3500 mm/year to 4500 mm/year) and residual soils. In addition, the area of interest has an average annual temperature of 23.5°C and an annual precipitation of 4200 mm (Harris et al., 2020). Certain areas of the slopes studied lack vegetation cover, porous lithology and heavy rainfall, develop ideal conditions for high infiltration rates, making them susceptible to landslides and soil erosion (Laraque et al., 2004; Bravo et al., 2017).

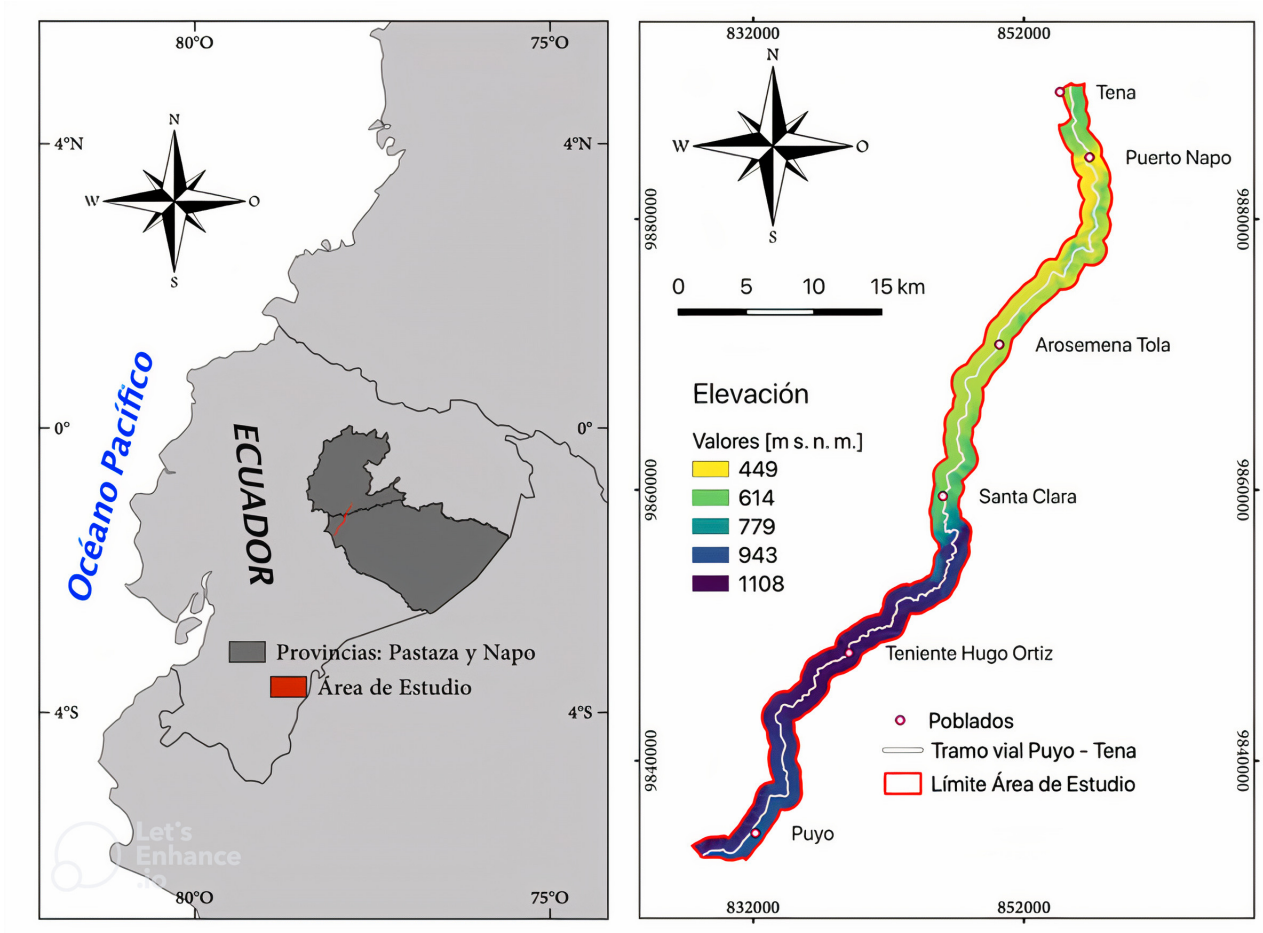

Figure 1. Location of the study area.

3 Materials and Methods

The Analytical Hierarchy Process (AHP) was used. AHP is a semi-quantitative method based on the evaluation of multi-criteria decision-making to treat complex and multi-attribute problems (Gudiyangada Nachappa et al., 2020). The analytical hierarchy process developed by Saaty (1990) disaggregates a

complex decision problem at different hierarchical levels and allows to quantify opinions and transform them into a coherent decision model. The process is based on four principles: (i) hierarchy development, (ii) peer comparison, (iii) judgment synthesis and (iv) consistency check. This method along with the weighted linear combination allows to have the graphical representation of the most susceptible zones to landslide. In the end, the process of analytical hierarchy confers the best choice for the decision-making (Mallick et al., 2018; Basu and Pal, 2020; Zhou et al., 2020). The process leading to the landslide susceptibility mapping model is detailed below.

3.1 Landslide Inventory

According to Wieczorek (1984), it is necessary to provide a landslide map to discern locations and specify landslides that have occurred with different spatial and temporal scales. Thus, a representative landslide database is a prerequisite for any landslide hazard or risk assessment (Varnes and International Association of Engineering Geology, 2021; Guzzetti et al., 1999); and a landslide susceptibility mapping model is no exception. Using orthophotographs as a base, landslides were identified which were later confirmed in the field by three days of travel (July 27th, 28th and 29th, 2021). In addition, as a result of the *in situ* tour other landslides were found. Each landslide found was georeferenced and characterized according to its lithology and type of landslide. In total, 62 landslides were identified along the highway of interest. The largest slides are shown in Table 1 and Figure 2.

Table 1. Representative part of the inventory of landslides found on the Puyo-Tena road.

Inventory	Degree-Decimal Coordinates		Geological	Slide
	Longitude	Latitude	Formation	Type
1	−77.8088°	−1.1159°	Arajuno	Rotational
2	−77.7947°	−1.0978°	Chalcana	Fall
3	−77.7933°	−1.0936°	Chalcana	Fall
4	−77.7905°	−1.0831°	Chalcana	Rotational
5	−77.7912°	−1.0789°	Tiyuyacu	Rotational

3.2 Preparation of the Layers of the Sliding Variables

All the information was collected from governmental and educational sources. This information is listed in Table 2. The variables to be considered in the susceptibility to landslides were geological formations, slope, geological faults, road construction, distance to rivers and land cover and use (hereinafter CUT). The selection of the six variables and their categories was based on the information obtained in the field and office. Similar studies in the region support the importance of taking into account this type of variables in the development of landslide susceptibility mapping models (Klimeš and Rios Escobar, 2010; Ortiz and Martínez-Graña, 2018; Barella et al., 2019; Orejuela and Toulkeridis, 2020; Vásquez, 2023). Categories refer to the different divisions of each variable; for example, the Napo, Tena, and Mera formations are categories of the variable geological formations. Subsequently, the selected variables were converted into thematic layers as an initial step in the development of the mapping model of susceptibility.

All subject layers were rasterized with a pixel resolution of 12.5 m. All the weights made for the six variables and their categories were selected according to the analyzes carried out in the field and office. The reclassifications for each thematic layer were performed based on the data obtained from each variable. Subsequently, the thematic layers were combined, analyzed with the AHP, using the Weighted Linear Combination (WLC) which is an analytical and hybrid method (qualitative and quantitative) used in GIS to process raster layers (Feizizadeh and Blaschke, 2013).

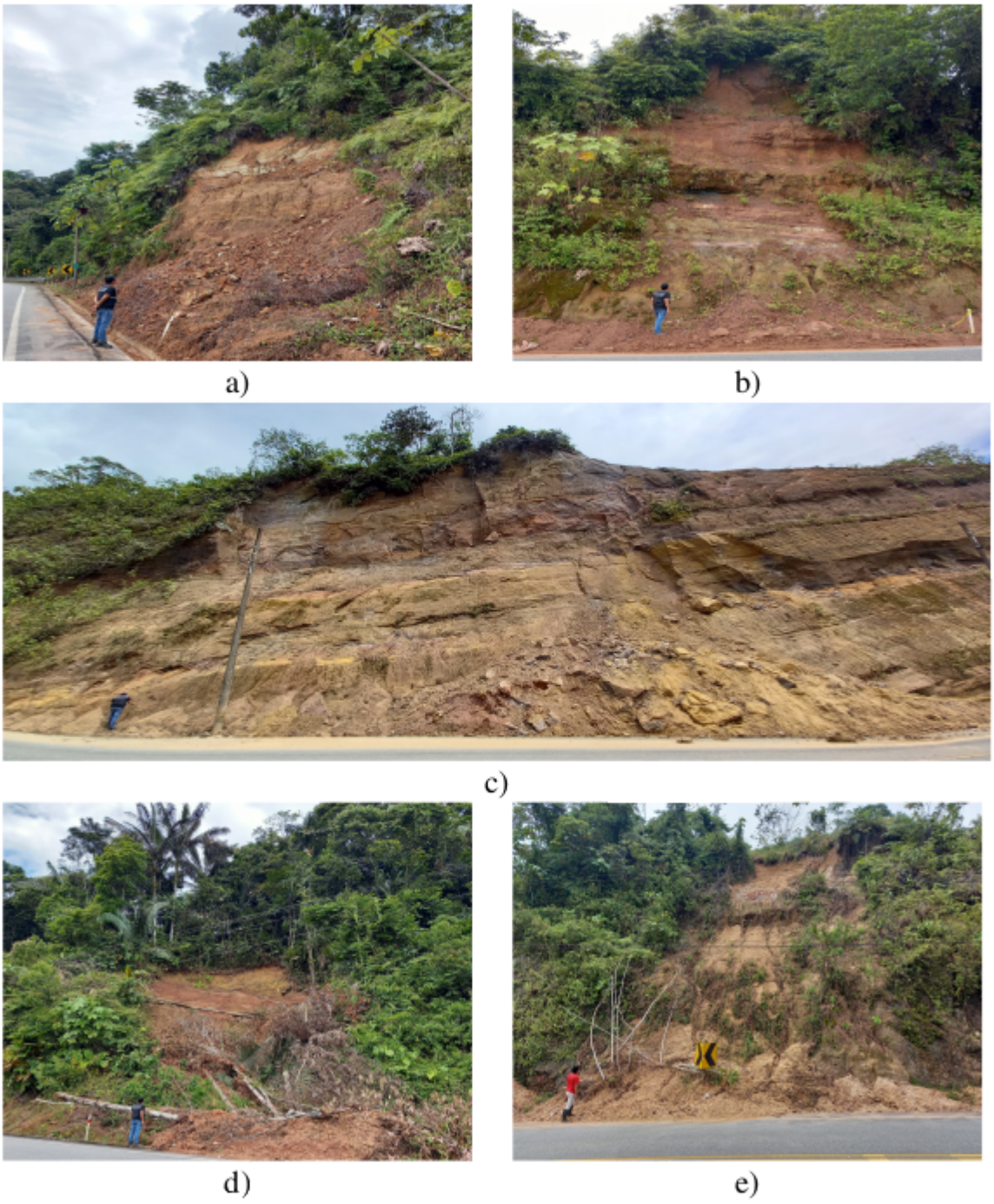

Figure 2. Landslides according to the inventory in Table 1: a) is 1, b) is 2, c) is 4, d) is 3 and e) is 5.

The distance to geological faults, roads and rivers were calculated using the buffer tool in QGIS. The slope was obtained from a Digital Elevation Model (DEM) of 12.5 m pixel resolution for the study area. All spatial analysis procedures were performed on the free software QGIS version 3.4 Madeira (Figure 3).

Table 2. Data sources used for the study.

Data	Description	Source
Orthophotos (Resolution 0.30 m)	Downloaded	SIGTIERRAS PROGRAM http://www.sigtierras.gob.ec/
Digital Elevation Model- DEM (Resolution 12.5 m)	Downloaded	ASF https://search.asf.alaska.edu/#/
Slope	Derived from the 12.5 m DEM	DEM 12.5 m
Geological Formations	Downloaded	MAGAP http://geoportal.agricultura.gob.ec/
Geological Faults	Downloaded	SARA PROJECT https://sara.openquake.org/start
Roads	Downloaded	IGM http://www.geoportaligm.gob.ec/portal/
Rivers	Downloaded	IGM http://www.geoportaligm.gob.ec/portal/
Land Cover and Land Use (CUT)	Downloaded	MAGAP http://geoportal.agricultura.gob.ec/

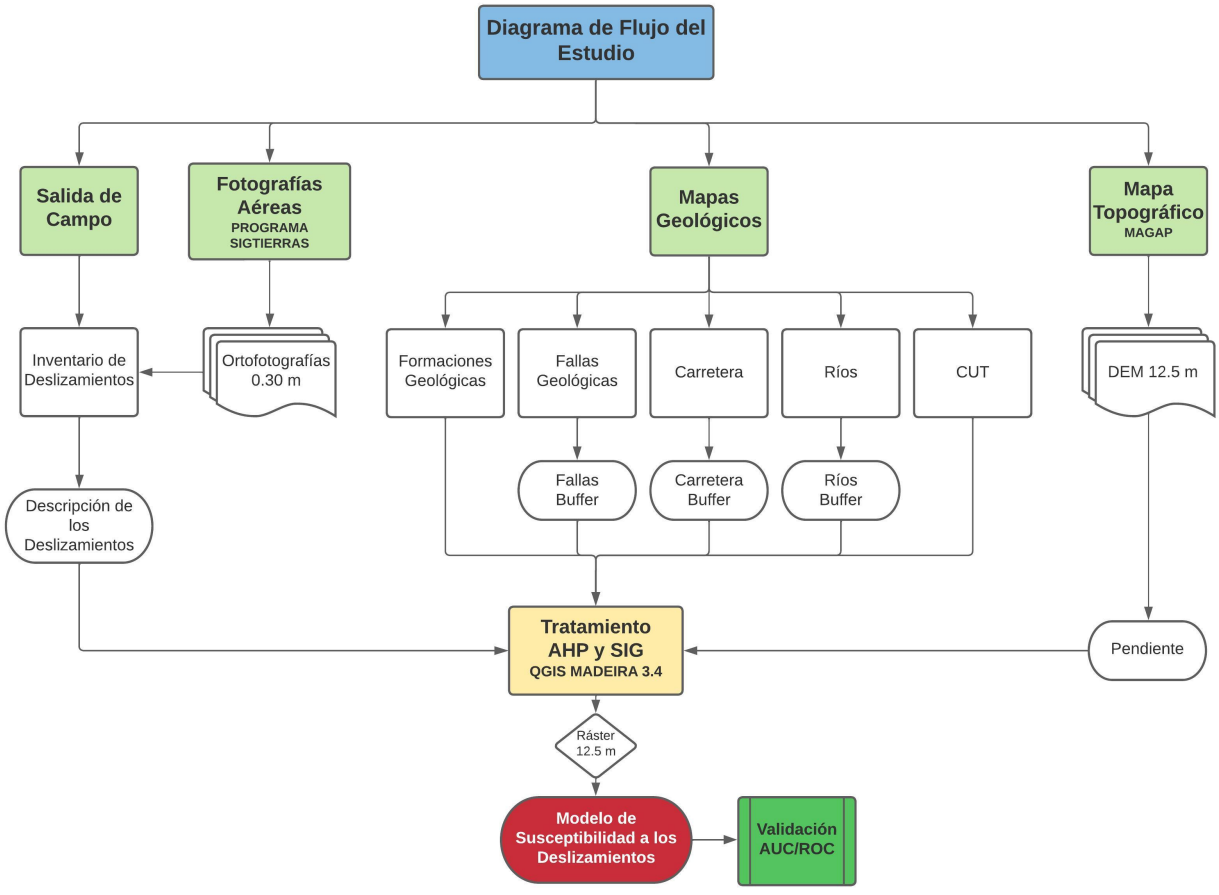

Figure 3. Flow Chart of the Study.

All vector subject layers were rasterized with pixel resolution of 12.5 m × 12.5 m. Rasterization allowed the six thematic layers to be combined and form a single raster layer. The pixel resolution of 12.5 m was selected because the DEM was worked with this spatial resolution. The procedure for each of the variables is detailed below.

Slope

The slope values were extracted from the DEM of 12.5 m pixel resolution. The slope is an indispensable variable, since depending on its inclination angle it will cause that there is greater or lesser susceptibility to landslides (Dolui et al., 2019; Nguyen et al., 2019; Bahrami et al., 2021). In this study, this topic layer was obtained using the QGIS gdaldem library; and it was categorized into six parts: $< 5^{\circ}$, 5– 12°, 12– 25°, 25– 40°, 40– 70° y >70° (Figure 4a). The categorization was based on the reclassification established by the data source (Table 2). The weight values and the other variables are detailed in the results.

Geological Formations

Geological formations depending on lithology, permeability and soil consolidation will greatly influence the likelihood of landslides (Althuwaynee and Pradhan, 2017; Salehpour Jam et al., 2021). For developing this thematic layer, a total of seven geological formations, alluvial deposits, colluvial deposits and others (without description) along the road of interest were recorded (Figure 4b). The categorization was based on observations from recent formations and deposited.

Distance to Geological Faults

Areas with active faults are susceptible to landslides (Demir et al., 2013; Ozdemir, 2020). The areas closest to this area are more likely to occur due to landslides, due to intense shear. For developing this thematic layer, distances to failure were categorized into five classes: <200 m, 200- 400 m, 400- 600 m, 600- 1000 m and >1000 m (Figure 4c). This categorization was based on observations of outcrops affected by the fault zones, which appeared up to 1000 m. In addition, the faults present in the study area correspond to quaternary faults, approximately <1.8 Ma.

Distance to Road

Roads located in slope areas condition that there is greater susceptibility to landslides, due to the presence of infrastructure, colonization process, emergence of new settlements and connections with other roads (Igwe et al., 2020; Panchal and Shrivastava, 2020). During the fieldwork, because of these four factors it was evident that there were outcrops affected located up to 750 m from the road line. For this reason, this thematic layer was categorized into four classes: <250 m, 250- 500 m, 500- 750 m and >750 m (Figure 4d).

Distance to rivers

Rivers erode the terrain, thus favoring landslides (Achour et al., 2017; Tešić et al., 2020). In the field, landslides located up to 750 m measured from the margin of the rivers were evidenced. There was a higher number of landslides near rivers and a higher displacement mass, compared to more distant regions where there was a lower number of landslides. Therefore, for this thematic layer, rivers were categorized into five classes: <50 m, 50- 250 m, 250- 500 m, 500- 750 m and >750 m (Figure 4e).

Land Cover and Use (CUT)

The CUT is an important variable involved in landslide processes. The removal of forests to convert them into grasslands, agricultural areas or areas of urban expansion, intensifies the erosion and flow of flows when there is precipitation. These events largely favor the occurrence of landslides (Guevara et al., 2020; Roccati et al., 2021). For the development of this last thematic layer, five land use categories were registered: Agriculture, Area without Vegetation Cover, Forest, Shrub Vegetation and Anthropic Zone (Figure 4f). Water bodies were excluded because they were analyzed in the distance to rivers variable.

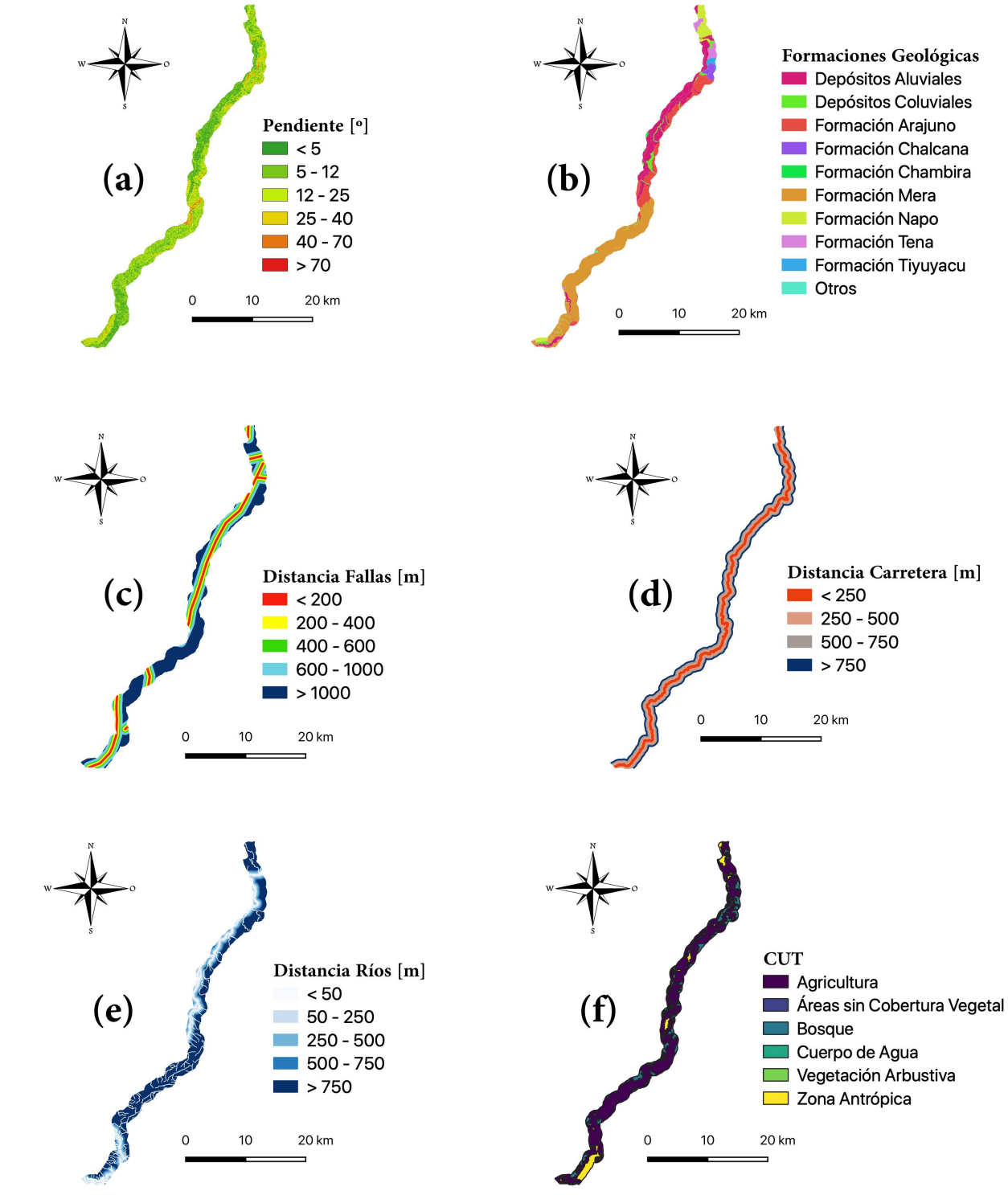

Figure 4. Thematic layers of variables along the Puyo - Tena road: (a) Slope, (b) Geological Formations, (c) Distance to Faults, (d) Distance to Road, (e) Distance to Rivers and (f) CUT.

3.3 Susceptibility Mapping

For the application of the AHP method, it is essential to assign a relative weight to the variables. Mathematical calculations to obtain the values of each step of the AHP were performed using the RStudio software. The steps used are described in detail below. a) Development of the hierarchical structure of the variables. b) Matrix of judgments by pair comparison. Relative weight according to Table 3 (Saaty, 1977). Applying the criterion of this table, it was decided which variable is more influential in relation to another variable. Priority was established and the six variables were weighted. (c) Synthesis of comparative judgements. Calculation of the final priority of each variable according to the table (Saaty, 1977). At this point the final normalized weighting of each variable was obtained, thus determining how much the variables contributed to meet the objective. d) Consistency evaluation. It allowed to verify if the weights of the comparative judgments had logic. e) Combination of thematic layers and obtaining the mapping model of susceptibility. f) Reclassification of the final mapping model of susceptibility.

Table 3. Fundamental Scale of Saaty (1977).

Value	Definition	Explanation
1	Equally important	Two decision items influence the main decision item equally.
3	Moderately more important	One decision element is moderately more influential than another.
5	Much more important	One decision element has more influence than another.
7	Really much more important	One decision-making element has a significantly greater influence than the other.
9	Extremely important	The difference in decision between the influences of the two decision elements is extremely significant.
2, 4, 6, 8	Intermediate Judgment Values	Values of judgment among equals, moderately, much, and extremely.

Once the weights were made, using the calculation of coherence or radius of coherence (*CR*), it was determined whether the calculation concluded correctly or not, described in the Eq (1). Thus, it was possible to recognize if there was coherence in the comparison of importance range of each variable.

$$CR = \frac{CI}{RI} \tag{1}$$

Where, *RI* (Table 4) refers to the random consistency index; instead,*CI* refers to the consistency index, described in Eq (2). The *RI* index is a defined value that is part of the AHP method.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Where,λ_{max} is the eigen maximum value and is calculated from the array and n is the order of the array. According to Saaty (1990), the coherence ratio must be less than or equal to 10% or an imprecision of less than 10%. The principle is to compare judgment with random comparison of elements. Finally, the weights integrated the different causal classes in a single index of susceptibility to landslides, LSI using the Eq (3) (Saaty, 1990).

$$LSI = \sum_{i=1}^{n} R_i * W_i \tag{3}$$

Where, R_i are the classification classes of each variable and W_i are the weights for each of the conditioning variables of the landslides. The resulting cartographic model *LSI* was reclassified into five susceptibility classes: very low, low, moderate, high, and very high. These five divisions were made according to the method of quantiles using the pixel values of the final cartographic model of susceptibility to landslides.

3.4 Validation of the Cartographic Model

An adequate validation is obtained by comparing the final mapping model, developed from the AHP method with the landslide inventory map (Basu and Pal, 2020; Ozdemir, 2020). The validation was performed using the Receiver Operating Characteristics (*ROC*) method, which has been widely used for this type of studies (Igwe et al., 2020; Bahrami et al., 2021; Salehpour Jam et al., 2021; Kincal and Kayhan, 2022).

The ROC curve is used to graphically show the correlation between the true-positive rate and the false-positive rate (Soeters and Van Westen, 1996; Williams et al., 1999; Althouse, 2016). The area under the curve (AUC) of the ROC curve, the closer it is to 1.0, the better the prediction of the mapping model; however, the closer it is to 0.5, the more unreliable the model will have a random prediction.

Table 4. Index of Random Consistency of Saaty (1990).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4 Results

4.1 Analytic Hierarchy Process

Hierarchy and pair comparison allowed to know the influence degree of the variables of landslides (Table 5). The most outstanding variables were slope, geological formations, distances to rivers and land cover and use, while the least influential were road distances and faults. The analysis of the coherence radius for each variable and for the final susceptibility cartographic model obtained a value lower than 0.10 (Table 5 and Table 6). These values reflect that the AHP procedure was performed correctly. After hierarchization, pair comparison, comparative judgments and consistency assessment, the final matrix was obtained with the weights of the six variables to make final landslide susceptibility model (Table 6).

The final landslide susceptibility model was reclassified into five classes: very low, low, moderate, high and very high (Figure 5). Based on data from the table (Table 7), the susceptibility area percentages were very low (0.64%), low (31.96%), moderate (50.87%), high (15.83%), and very high (0.70%). Once the model was completed, it was found that there are fifteen regions in the Puyo-Tena road with high and very high susceptibility classes (Figure 5 and Table 8), where four of them are located near the towns of Puyo, Santa Clara, Arosemena Tola and Puerto Napo. The 15 regions were selected after observation and analysis of the final model. The inventoried landslides were placed on the final cartographic model and most of them were located within these fifteen regions of high and very high susceptibility to landslides.

4.2 Validation of the Cartographic Model

The "ROCR" library of the "ROCR" package was used in the RStudio software to evaluate the accuracy of our landslide susceptibility mapping model. Analysis of the ROC curve revealed an AUC of 0.837, indicating a predictive accuracy of 83.7% (Figure 6). This metric is a reliable measure to evaluate the performance of the model in predicting landslides.

Table 5. Matrix of hierarchy and pairs comparison of variables.

Variables	Categories	Weighting Categories	Variables Weighting	Weights Categories	CR Variables
Geological Formations	Alluvial Deposit	2	7	0.039	0.0032
	Tena Formation	8		0.154	
	Mera Formation	7		0.135	
	Arajuno Formation	8		0.154	
	Chambira Formation	6		0.115	
	Napo Formation	5		0.097	
	Tiyuyacu Formation	6		0.115	
	Chalcana Formation	5		0.097	
	Coluviall Deposit	4		0.077	
	Otros	1		0.020	
Failures	<200	9	2	0.359	0.0011
	200 – 400	7		0.280	
	400 – 600	5		0.199	
	600 – 1000	3		0.120	
	>1000	1		0.039	
Slope	<5°	1	9	0.039	0.0028
	5 – 12°	2		0.077	
	12 – 25°	4		0.154	
	25 – 40°	5		0.193	
	40 – 70 °	8		0.308	
	>70°	6		0.230	
Distance to Roads	<250	7	3	0.411	0.0033
	250 – 500	5		0.294	
	500 – 750	3		0.176	
	>750	2		0.118	
Distance to Rivers	<50	9	6	0.375	0.0017
	50 – 250	7		0.292	
	250 – 500	4		0.167	
	500 – 750	3		0.125	
	>750	1		0.043	
CUT	Agriculture	7	5	0.368	0.0039
	Vegetation Uncovered Area	1		0.053	
	Forest	4		0.211	
	Shrub Vegetation	5		0.263	
	Anthropic Zone	2		0.105	

Table 6. Pair comparison matrix and final weighting of each landslide variable.

	Peer Comparison Matrix						Weighting	Final CR
	Slope	Geological Formations	Rivers	CUT	Roads	Failures		
Slopes	1.00						0.281	0.0039
Geological Formations	0.78	1.00					0.219	
Rivers	0.67	0.86	1.00				0.187	
CUT	0.56	0.72	0.84	1.00			0.157	
Roads	0.34	0.43	0.50	0.60	1.00		0.094	
Failures	0.23	0.29	0.34	0.40	0.67	1.00	0.063	

5 Discussion

In this research, the GIS-based AHP method was used as a multicriteria evaluation method to identify areas susceptible to landslides on the Puyo-Tena road. The data presented from the six variables show how they influence landslide susceptibility along the study road; similar situation was observed in Hepdeniz (2020) and Chanu and Bakimchandra (2022). As a result of hierarchization, peer weighting, comparative judgments and the value obtained in the consistency radius (CR <0.1), the weights made in the variables are reliable and were correctly performed. In addition, with the validation of the cartographic model using the area under the AUC curve of the ROC curve, 0.837 was obtained, supporting that the quality of the susceptibility landslide model is very good (Roy and Saha, 2019; Sonker et al., 2021).

Compared to similar studies carried out on roads in other countries, different results were observed than those obtained in this research. The Indian road studied by Panchal and Shrivastava (2022) showed a value close to our study, with an AUC of 0.825. On the other hand, the China-Pakistan road studied by Ali et al. (2019), obtained an AUC of 0.72, while the road studied in Algeria by Achour et al. (2017), achieved an AUC value of 0.66. This brief comparison reveals the variability of AUC values in studies conducted in different regions of the world. This variation will be related to the number of landslides inventoried and the quality of the final landslide susceptibility mapping model.

According to the 1000 m buffer analyzed along the study road, 16.53% (25.38 km^2) correspond to potential regions for landslides distributed 15.83% (24.31 km) in high and 0.70% (1.07 km) in very high susceptibility. The rest, approximately 83.57% (128.14 km^2) of the road, does not represent a great risk for a possible landslide.

Table 7. Areas of categories of the landslide susceptibility mapping model.

Susceptibility Categories	Area [km^2]	Area [%]
Very Low	0.97	0.64
Low	49.07	31.96
Moderate	78.10	50.87
High	24.31	15.83
Very High	1.07	0.70
Total	153.52	100%

According to the landslide susceptibility LSI mapping model (Figure 5) and the data shown in Table 8, approximately 17 km of approximately 80 km of the Puyo- Tena road are landslide susceptible, i.e., 21.25% of the road is landslide-susceptible. Once analyzed the variables *in situ* and digitally, it was determined that the four most important variables to intervene in landslide processes in this study site are slope, geological formations, distances to rivers and CUT; on the contrary, the remaining two variables, distance to road and distance to faults, are the ones that have less influence. For this research the analyzed variables have this hierarchy, but as He and Beighley (2008) mention, perhaps in other conditions and another area of study, the less influential variables could be more determinant. For example, if a road under construction is passing through steep mountains (Pourghasemi et al., 2012), or if the study area is near areas of active fault causing earthquakes (Abedini et al., 2017), they would be the main variables for landslide susceptibility.

Table 8. Main regions of the Puyo- Tena road with high and very high susceptibility to landslides.

Region	km [Home]	Degree-Decimal Coordinates		km [End]	Degree-Decimal Coordinates	
		Longitude	Latitude		Longitude	Latitude
1	0.125	-78.0500	-1.5088	3.692	-78.0236	-1.4993
2	14.163	-77.9987	-1.4235	14.275	-77.9988	-1.4225
3	29.018	-77.9238	-1.3486	29.329	-77.9224	-1.3465
4	36.498	-77.8880	-1.3119	36.765	-77.8858	-1.3111
5	38.933	-77.8822	-1.2963	39.679	-77.8840	-1.2914
6	41.097	-77.8897	-1.2853	42.424	-77.8898	-1.2746
7	44.583	-77.8886	-1.2569	48.331	-77.8821	-1.2304
8	56.780	-77.8547	-1.1634	57.653	-77.8511	-1.1568
9	59.150	-77.8425	-1.1470	60.820	-77.8328	-1.1361
10	63.517	-77.8169	-1.1197	63.938	-77.8137	-1.1217
11	66.121	-77.8053	-1.1076	66.700	-77.8018	-1.1042
12	67.864	-77.7920	-1.1051	68.886	-77.7947	-1.0973
13	70.238	-77.7901	-1.0871	70.937	-77.7916	-1.0812
14	72.836	-77.7904	-1.0657	73.655	-77.7912	-1.0597
15	75.536	-77.7966	-1.0459	76.381	-77.7951	-1.0391

Based on the results, it is determined that there are fifteen regions of the road with a high probability of landslides (Figure 5 and Table 8). Most of these regions are located outside the main towns except for regions 1, 6, 8 and 15, which are located near the towns of Puyo, Santa Clara, Arosemena Tola and Puerto Napo, respectively. Despite the proximity, it does not represent a latent risk to the inhabitants of these sectors. For this study, the slope is the most important variable because most of the landslides inventoried show features of being influenced by the upwelling inclination; similar scenario in the studies carried out by Dolui et al. (2019) and Bahrami et al. (2021).

Most landslides occur in areas with slopes >40°, specifically in the range of 40°- 70°. Geological formations are considered the second important incidence variable, since their lithological constitution, geomechanical resistance and porosity are involved in the occurrence of landslides. The physical conditions of each geological formation have different influences for the appearance of landslides. Geological formations, such as Chambira, Tiyuyacu, Mera, Tena and Arajuno, have porous lithology, low geomechanical resistance and low resistance to permeability; for this reason, they have a large number of landslides. Rivers are the third important variable. The different rivers cross different areas of high and low slope, thus favoring soil erosion and loss in soil resistance. Most landslides were found near the rivers, giving a clear idea that it is an important variable in landslide processes. Finally, CUT is also considered an important variable. Land-use change causes soil degradation, loss of mechanical strength, and increased water infiltration and therefore greater susceptibility to landslides. All these aspects are influenced by anthropic activities, which are clearly observed along the Puyo- Tena road. In contrast, the distance to the road and the distance to faults have the least influence on landslides. There is a lot of traffic in the road Puyo - Tena, but the movements originated by vehicles or human activities do not influence to a great extent the landslides.

Geological faults are triggers of earthquakes, which generate ground movements. Earthquakes in the Amazon are not too frequent compared to other regions of the country, and the effects have been slight (Rivadeneira et al., 2007). On the study road these earthquakes have low magnitude and little periodicity and do not have great impact for landslides. For this reason, these two variables are the ones that least influence the occurrence of landslides in the study area.

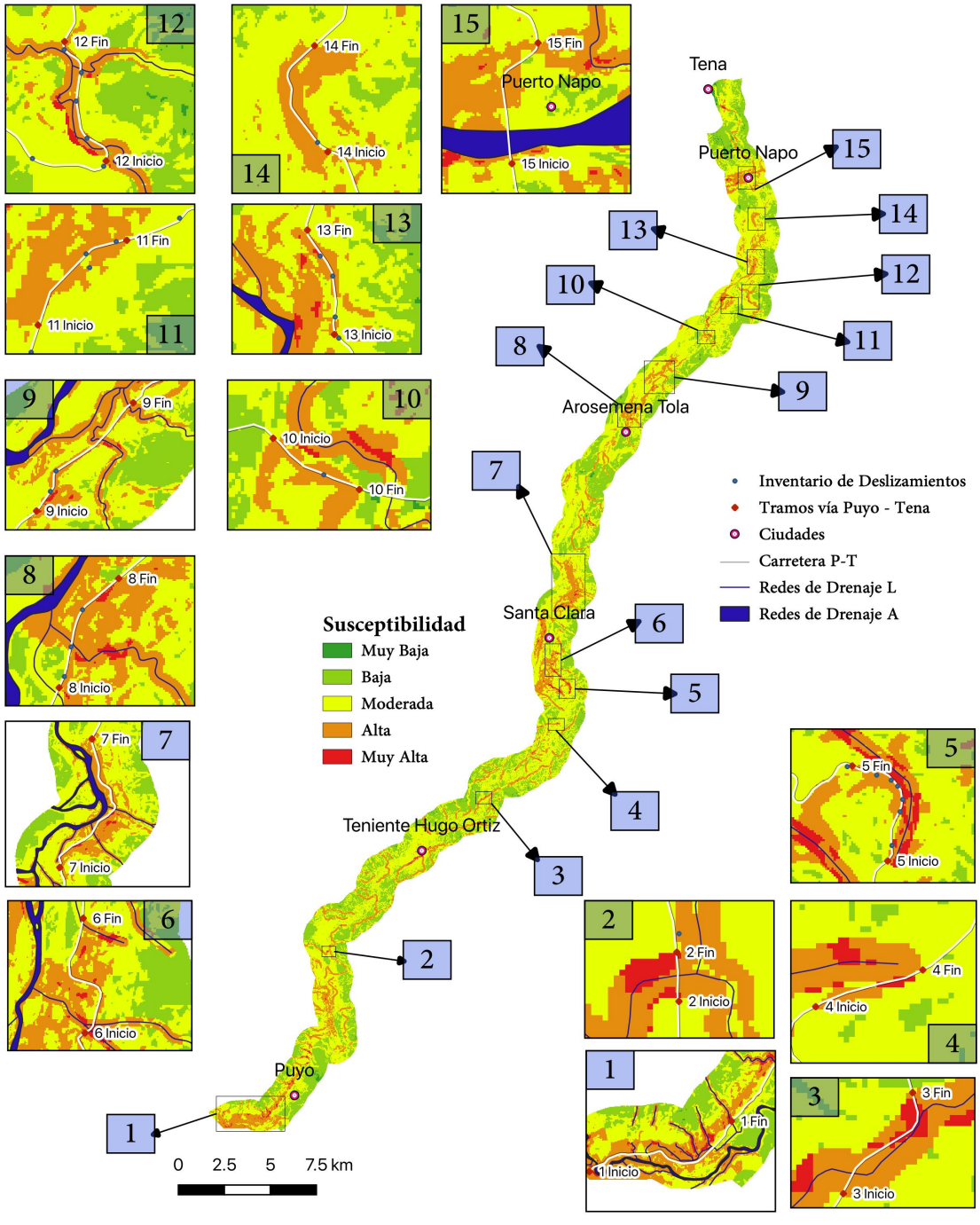

Figure 5. Landslide Susceptibility LSI cartographic model using the AHP method. Regions of the Puyo- Tena road.

Finally, new cartographic methods have been developed in recent decades for analyzing the susceptibility to landslides such as logistic regression, neural networks, *machine learning* and AHP, which is a method based on landslide inventories and statistical analysis, multicriteria, expert judgment, hierar-

chization, among others. Six variables that are commonly present in landslide processes were taken into account. The hierarchization of each of them was subject to the landslide inventory and the knowledge of the study area. From the four principles of the AHP method it was possible to obtain a mapping LSI model of susceptibility to landslides, and thus determine the main regions susceptible to landslides of the Puyo- Tena road.

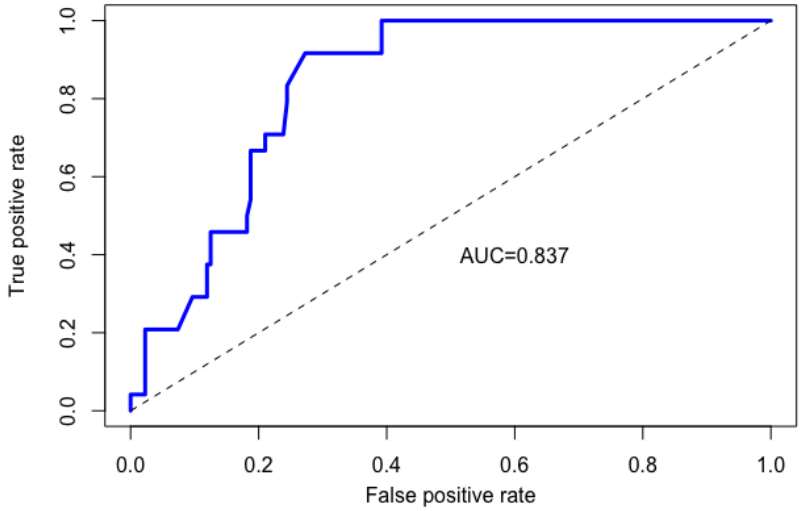

Figure 6. The ROC curve of the landslide susceptibility mapping model using the AHP method.

6 Conclusions

The susceptibility to landslides on the Puyo- Tena road, assessed by the AHP method, allowed a quick and practical manipulation of the physical data of the study area. The mapping LSI susceptibility model was obtained through the hierarchization, weighting and digitalization of the six variables involved in the research. Validation via the AUC/ROC method yielded a value of 0.837 corresponding to a predictive accuracy of 83.7%, supporting the quality of the cartographic model developed. The application of the AHP method allowed to identify the most influential variables, which were slope, geological formations, distances to rivers and land cover and use. Firsthand, the LSI model was reclassified into five susceptibility classes, obtaining surfaces of 0.64%, 31.96%, 50.87%, 15.83% and 0.70% for the classes of very low, low, moderate, high and very high, respectively. It was determined that approximately 17 km of the approximately 80 km of the Puyo-Tena road are susceptible to landslides, i.e. 21.25% of the road has potential to landslides. In addition, it was known that the studied road has 15 regions between high and very high probability for landslides. These regions were located on areas of high slope, porous and permeable lithology, a large number of rivers and soils suitable for agriculture. In addition, regions 1, 6, 8 and 15 were located near the towns of Puyo, Santa Clara, Arosemena Tola and Puerto Napo, respectively. These regions, despite their proximity to the towns, apparently do not represent a risk to the inhabitants of the sector.

The landslide susceptibility mapping model provides information consistent with the landslide inventory collected in the field. This model can be operated by governmental or non-governmental institutions that aim at land use planning and land management or similar purposes. The susceptibility model will allow decisions to avoid potential dangers that threaten the life and well-being of the population, plan an efficient road network, consider the best options for urban and rural expansion, including developing construction policies adjacent to the roads.

Author Contributions

CJCQ; Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Research, Methodology, Project Management, Resources, Software, Supervision, Validation, Visualization, Writing–original draft and Writing–review and editing. JREC; Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Research, Methodology, Project Administration, Supervision, Validation, Writing-original draft and Writing-review and editing. BGVC; Conceptualization, Data Curation, Formal Analysis, Research, Methodology, Supervision and Validation. MVST; Conceptualization, Research and Methodology. JSAS; Conceptualization, Research and Methodology. ECCB; Research, Resources, Software, Writing-original draft, Writing-review and editing. ADOC; Research, Resources and Software.

References

Abedini, M., Ghasemyan, B., and Rezaei, M. (2017). Landslide susceptibility mapping in bijar city, kurdistan province, iran: a comparative study by logistic regression and ahp models. *Environmental earth sciences*, 76:1–14. Online:https://n9.cl/ghgby.

Achour, Y., Boumezbeur, A., Hadji, R., Chouabbi, A., Cavaleiro, V., and Bendaoud, E. (2017). Landslide susceptibility mapping using analytic hierarchy process and information value methods along a highway road section in constantine, algeria. *Arabian Journal of Geosciences*, 10:1–16. Online:https://n9.cl/ggext0.

Ali, S., Biermanns, P., Haider, R., and Reicherter, K. (2019). Landslide susceptibility mapping by using a geographic information system (gis) along the china–pakistan economic corridor (karakoram highway), pakistan. *Natural Hazards and Earth System Sciences*, 19(5):999–1022. Online:https://n9.cl/3qz9h.

Althouse, A. (2016). Statistical graphics in action: making better sense of the roc curve. *International Journal of Cardiology*, 215:9–10. Online:https://n9.cl/hipk6.

Althuwaynee, O. and Pradhan, B. (2017). Semi-quantitative landslide risk assessment using gis-based exposure analysis in kuala lumpur city. *Geomatics, Natural Hazards and Risk*, 8(2):706–732. Online:https://n9.cl/44j52.

Asmare, D. (2023). Application and validation of ahp and fr methods for landslide susceptibility mapping around choke mountain, northwestern ethiopia. *Scientific African*, 19:e01470. Online:https://n9.cl/7vjlh.

Bahrami, Y., Hassani, H., and Maghsoudi, A. v. (2021). Landslide susceptibility mapping using ahp and fuzzy methods in the gilan province, iran. *GeoJournal*, 86:1797–1816. Online:https://n9.cl/frz7v.

Barella, C., Sobreira, F., and Zêzere, J. (2019). A comparative analysis of statistical landslide susceptibility mapping in the southeast region of minas gerais state, brazil. *Bulletin of Engineering Geology and the Environment*, 78:3205–3221. Online:https://n9.cl/z8lcl2.

Basu, T. and Pal, S. (2020). A gis-based factor clustering and landslide susceptibility analysis using ahp for gish river basin, india. *Environment, development and sustainability*, 22:4787–4819. Online:https://n9.cl/uh67s2.

Benchelha, S., Aoudjehane, H., Hakdaoui, M., El Hamdouni, R., Mansouri, H., Benchelha, T., Layelmam, M., and Alaoui, M. (2020). Landslide susceptibility mapping in the commune of oudka, taounate province, north morocco: A comparative analysis of logistic regression, multivariate adaptive regression spline, and artificial neural network models. *Environmental & Engineering Geoscience*, 26(2):185–200. Online:https://n9.cl/fxlus.

Bien, T., Truyen, P. T., Phong, T., Nguyen, D., Amiri, M., Costache, R., Duc, D., Le, H., Nguyen, H., and Prakash, I. (2022). Landslide susceptibility mapping at sin ho, lai chau province, vietnam using ensemble models based on fuzzy unordered rules induction algorithm. *Geocarto International*, 37(27):17777–17798. Online:https://bit.ly/3QWPHxw.

Bragagnolo, L., da Silva, R., and Grzybowski, J. (2020). Landslide susceptibility mapping with r. landslide: A free open-source gis-integrated tool based on artificial neural networks. *Environmental Modelling & Software*, 123:104565. Online:https://n9.cl/2lss7i.

Bravo, C., Torres, B., Alemán, R., and Marín, H. (2017). Indicadores morfológicos y estructurales de calidad y potencial de erosión del suelo bajo diferentes usos de la tierra en la amazonía ecuatoriana. *Anales de Geografia de la Universidad Complutense*, 37(2):247–264. Online:https://n9.cl/2lss7i.

Bravo-López, E., Fernández Del Castillo, T., Sellers, C., and Delgado-García, J. (2022). Landslide susceptibility mapping of landslides with artificial neural networks: Multi-approach analysis of backpropagation algorithm applying the neuralnet package in cuenca, ecuador. *Remote Sensing*, 14(14):3495. Online:https://n9.cl/zihph.

Carrara, A. (1983). Multivariate models for landslide hazard evaluation. *Journal of the International Association for Mathematical Geology*, 15:403–426. Online:https://n9.cl/ij7ke.

Chanu, M. and Bakimchandra, O. (2022). Landslide susceptibility assessment using ahp model and multi resolution dems along a highway in manipur, india. *Environmental Earth Sciences*, 81(5):156. Online:https://n9.cl/55hjo.

Correo (2017). Tramos de 21 vías de once provincias siguen cerrados. Noticias Correo. Online:https://bit.ly/49Kw8Po.

Cruden, D. (1991). A simple definition of a landslide. *Bulletin of Engineering Geology & the Environment*, 43(1):27–29. Online:https://n9.cl/b5nhdd.

Cruden, D. and Varnes, D. (1996). *Landslides: investigation and mitigation*, chapter Chapter 3 - Landslide types and processes, pages 36–75. Transportation Research Board.

Dahal, B. and Dahal, R. (2017). Landslide hazard map: tool for optimization of low-cost mitigation. *Geoenvironmental Disasters*, 4:1–9. Online:https://n9.cl/xd5dr.

Dai, F., Lee, C., Li, J., and Xu, Z. (2001). Assessment of landslide susceptibility on the natural terrain of lantau island, hong kong. *Environmental geology*, 40:381–391. Online:https://n9.cl/pktic.

Demir, G., Aytekin, M., Akgün, A., Ikizler, S., and Tatar, O. (2013). A comparison of landslide susceptibility mapping of the eastern part of the north anatolian fault zone (turkey) by likelihood-frequency ratio and analytic hierarchy process methods. *Natural hazards*, 65:1481–1506. Online:https://n9.cl/4vxpj.

Dolui, B., Yuvaraj, R., and Geetha, G. (2019). Landslide susceptibility mapping using ahp model in nilgiri district. *Thematics Journal of Geography*, 8(12):189–208. Online:https://n9.cl/vy1ht.

Ecoamazónico (2014). Mtop atiende inmediatamente los 6 deslizamientos de tierra. Ecoamazónico. Online:http://t.ly/eezh .

Ecoamazónico (2020). Reporte de un derrumbe en la vía al tena. Ecoamazónico. Online:http://t.ly/n45D .

Ecoamazónico (2021). Vía habilitada en el paso lateral. Ecoamazónico. Online:http://t.ly/YDmXR .

Ercanoglu, M. and Gokceoglu, C. (2004). Use of fuzzy relations to produce landslide susceptibility map of a landslide prone area (west black sea region, turkey). *Engineering geology*, 75(3-4):229–250. Online:https://n9.cl/gyhr2c.

Feizizadeh, B. and Blaschke, T. (2013). Gis-multicriteria decision analysis for landslide susceptibility mapping: comparing three methods for the urmia lake basin, iran. *Natural hazards*, 65:2105–2128. Online:https://n9.cl/qlba92.

Gameiro, S., de Oliveira, G., and Guasselli, L. (2022). The influence of sampling on landslide susceptibility mapping using artificial neural networks. *Geocarto International*, pages 1–23. Online:https://n9.cl/qiex9x.

Gobierno Cantonal de Pastaza (2020). *Plan de Desarrollo y Ordenamiento Territorial del cantón Pastaza 2020-2030*. Gobierno Cantonal de Pastaza.

Gobierno Provincial de Napo (2020). *Plan de Desarrollo y Ordenamiento Territorial Napo 2020-2023*. Gobierno Provincial de Napo.

Gudiyangada Nachappa, T., Kienberger, S., Meena, S., Hölbling, D., and Blaschke, T. (2020). Comparison and validation of per-pixel and object-based approaches for landslide susceptibility mapping. *Geomatics, Natural Hazards and Risk*, 11(1):572–600. Online:https://n9.cl/bxnw9.

Guevara, M. d. J., Carbajal, N., and Tuxpan Vargas, J. (2020). Soil deterioration in the southern

chihuahuan desert caused by agricultural practices and meteorological events. *Journal of Arid Environments*, 176:104097. Online:https://n9.cl/j313s.

Guillen, K., Mendoza, M., Macías, J., and Solis-Castillo, B. (2022). Landslide susceptibility analysis based on a semiquantitative method in the sierra-costa region, michoacán, mexico. *Physical Geography*, 43(4):463–486. Online:https://n9.cl/84ebbv.

Guzzetti, F., Carrara, A., Cardinali, M., and Reichenbach, P. (1999). Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, central italy. *Geomorphology*, 31(1-4):181–216. Online:https://bit.ly/3udcJaq.

Hamza, T. and Raghuvanshi, T. (2017). Gis based landslide hazard evaluation and zonation–a case from jeldu district, central ethiopia. *Journal of King Saud University-Science*, 29(2):151–165. Online:https://n9.cl/i8u6e.

Harris, I., Osborn, T., Jones, P., and Lister, D. (2020). Version 4 of the cru ts monthly high-resolution gridded multivariate climate dataset. *Scientific data*, 7(1):109. Online:https://n9.cl/6huao.

He, Y. and Beighley, R. (2008). Gis-based regional landslide susceptibility mapping: a case study in southern california. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 33(3):380–393. Online:https://n9.cl/977ea.

Hearn, G. and Hart, A. (2019). Landslide susceptibility mapping: a practitioner's view. *Bulletin of Engineering Geology and the Environment*, 78(8):5811–5826. Online:https://n9.cl/kvril.

Hepdeniz, K. (2020). Using the analytic hierarchy process and frequency ratio methods for landslide susceptibility mapping in isparta-antalya highway (d-685), turkey. *Arabian Journal of Geosciences*, 13(16):795. Online:https://n9.cl/dzcxg.

Igwe, O., John, U., Solomon, O., and Obinna, O. (2020). Gis-based gully erosion susceptibility modeling, adapting bivariate statistical method and ahp approach in gombe town and environs northeast nigeria. *Geoenvironmental Disasters*, 7:1–16. Online:https://n9.cl/9d7nz.

Jamir, M., Chang, C., Jamir, I., Thong, G., and Walling, T. (2022). Landslide susceptibility mapping of noklak town, nagaland, north-east india using bivariate statistical method. *Geological Journal*, 57(12):5250–5264. Online:https://n9.cl/q0qdk.

Kincal, C. and Kayhan, H. (2022). A combined method for preparation of landslide susceptibility map in izmir (türkiye). *Applied Sciences*, 12(18):9029. Online:https://n9.cl/u3cks.

Klimeš, J. and Rios Escobar, V. (2010). A landslide susceptibility assessment in urban areas based on existing data: an example from the iguaná valley, medellín city, colombia. *Natural Hazards and Earth System Sciences*, 10(10):2067–2079. Online:https://n9.cl/v4r15.

Komac, M. (2006). A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine slovenia. *Geomorphology*, 74(1-4):17–28. Online:https://n9.cl/gw7og.

Laraque, A., Ceron, C., Armijos, E., Pombosa, R., Magat, P., and Guyot, J. (2004). *ediment Transfer through the fluvial system*, volume 288, chapter Sediment yields and erosion rates in the Napo River Basin: an Ecuadorian Andean Amazon tributary, pages 220–225. Online:https://bit.ly/3MH0nOd. IAHS.

Lee, S. and Min, K. (2001). Statistical analysis of landslide susceptibility at yongin, korea. *Environmental Geology*, 40(9):1095–1113. Online:https://bit.ly/3tzABol.

Mallick, J., Singh, R., AlAwadh, M., Islam, S., Khan, R., and Qureshi, M. (2018). Gis-based landslide susceptibility evaluation using fuzzy-ahp multicriteria decision-making techniques in the abha watershed, saudi arabia. *Environmental Earth Sciences*, 77:1–25. Online:https://n9.cl/uuy8p.

Mansouri Daneshvar, M. (2014). Landslide susceptibility zonation using analytical hierarchy process and gis for the bojnurd region, northeast of iran. *Landslides*, 11(6):1079–1091. Online:https://n9.cl/2azojx.

Ministerio del Ambiente de Ecuador (2014). *Sistema de Clasificación de Ecosistemas del Ecuador Continental*. Ministerio del Ambiente de Ecuador.

Nguyen, V., Pham, B., Vu, B., Prakash, I., Jha, S., Shahabi, H., Shirzadi, A., Ba, D., Kumar, R., Chatterjee, J., and Bui, D. (2019). Hybrid machine learning approaches for landslide susceptibility modeling. *Forests*, 10(2):157. Online:https://n9.cl/2i4cc.

Nhu, V., Shirzadi, A., Shahabi, H., Singh, S., Al-Ansari, N., Clague, J., Jaafari, A., Chen, W., Miraki, S., Dou, J., Luu, C., Górski, K., Pham, B., Nguyen, H., and Ahmad, B. (2020). Shallow landslide susceptibility mapping: A comparison between logistic model tree, logistic regression, naïve bayes tree, artificial neural network, and support vector machine algorithms. *International journal of environmental research and public health*, 17(8):2749. Online:https://n9.cl/am82bp.

Nicu, I. and Asăndulesei, A. (2018). Gis-based evaluation of diagnostic areas in landslide susceptibility analysis of bahluieț river basin (moldavian plateau, ne romania). are neolithic sites in danger? *Geomorphology*, 314:27–41. Online:https://n9.cl/71hsz.

Nilsen, T., Wright, R., Geological, U., Vlasic, T., Spangle, W., and Spangle, W. (1979). *Relative slope stability and land-use planning. Selected examples from the San Francisco Bay region, California*. Ministerio del Ambiente de Ecuador.

Obras Públicas Ecuador (2022). Trabajamos con maquinaria y personal en coordinación con @gadpastaza y gad de santa clara debido a un deslizamiento en el sector. Twitte r. Online:http://t.ly/B3fX .

Okoli, J., Nahazanan, H., Nahas, F., Kalantar, B., Shafri, H., and Khuzaimah, Z. (2023). High-resolution lidar-derived dem for landslide susceptibility assessment using ahp and fuzzy logic in serdang, malaysia. *Geosciences*, 13(2):34. Online:https://n9.cl/43tlc.

Orejuela, I. and Toulkeridis, T. (2020). Evaluation of the susceptibility to landslides through diffuse logic and analytical hierarchy process (ahp) between macas and riobamba in central ecuador. In *2020 Seventh International Conference on eDemocracy y eGovernment (ICEDEG)*, pages 201–207.

Ortiz, J. and Martínez-Graña, A. (2018). A neural network model applied to landslide susceptibility analysis (capitanejo, colombia). *Geomatics, Natural Hazards & Risk*, 9(1):1106–1128. Online:https://n9.cl/hg8r7.

Ozdemir, A. (2020). A comparative study of the frequency ratio, analytical hierarchy process, artificial neural networks and fuzzy logic methods for landslide susceptibility mapping: Taşkent (konya), turkey. *Geotechnical and Geological Engineering*, 38:4129–4157. Online:https://n9.cl/w77582.

Ozturk, D. and Uzel-Gunini, N. (2022). Investigation of the effects of hybrid modeling approaches, factor standardization, and categorical mapping on the performance of landslide susceptibility mapping in van, turkey. *Natural Hazards*, 114(3):2571–2604. Online:https://n9.cl/f0ct7.

Panchal, S. and Shrivastava, A. (2020). Application of analytic hierarchy process in landslide susceptibility mapping at regional scale in gis environment. *Journal of Statistics and Management Systems*, 23(2):199–206. Online:https://n9.cl/7uzpk.

Panchal, S. and Shrivastava, A. (2022). Landslide hazard assessment using analytic hierarchy process (ahp): A case study of national highway 5 in india. *Ain Shams Engineering Journal*, 13(3):101626. Online:https://n9.cl/b2pkh.

Pham, Q., Achour, Y., Ali, S., Parvin, F., Vojtek, M., Vojteková, J., Al-Ansari, N., Achu, A., Costache, R., Khedher, K., and Anh, D. (2021). A comparison among fuzzy multi-criteria decision making, bivariate, multivariate and machine learning models in landslide susceptibility mapping. *Geomatics, Natural Hazards and Risk*, 12(1):1741–1777. Online:https://n9.cl/719xzd.

Pourghasemi, H., Pradhan, B., and Gokceoglu, C. (2012). Application of fuzzy logic and analytical hierarchy process (ahp) to landslide susceptibility mapping at haraz watershed, iran. *Natural hazards*, 63:965–996. Online:https://n9.cl/l2h6a.

Pourghasemi, H., Teimoori Yansari, Z., Panagos, P., and Pradhan, B. (2018). Analysis and evaluation of landslide susceptibility: a review on articles published during 2005–2016 (periods of 2005-2012 and 2013-2016). *Arabian Journal of Geosciences*, 11:1–12. Online:https://n9.cl/06bsn.

Raghuvanshi, T., Ibrahim, J., and Ayalew, D. (2014). Slope stability susceptibility evaluation parameter (ssep) rating scheme–an approach for landsli-

de hazard zonation. *Journal of African Earth Sciences*, 99:595–612. Online:https://n9.cl/zxw0it.

Rivadeneira, F., Segovia, M., Alvarado, A., Egred, J., Troncoso, L., Vaca, S., and Yepes, H. (2007). *Breves fundamentos sobre los terremotos en el Ecuador*. Corporación Editora Nacional.

Roccati, A., Paliaga, G., Luino, F., Faccini, F., and Turconi, L. (2021). Gis-based landslide susceptibility mapping for land use planning and risk assessment. *Land*, 10(2):162. Online:https://n9.cl/oke3i.

Roy, J. and Saha, S. (2019). Landslide susceptibility mapping using knowledge driven statistical models in darjeeling district, west bengal, india. *Geoenvironmental Disasters*, 6(1):1–18. Online:https://n9.cl/ro35j.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology*, 15(3):234–281. Online:https://n9.cl/zvwbr.

Saaty, T. L. (1990). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. Analytic hierarchy process series. RWS Publications.

Salcedo, D., Padilla Almeida, O., Morales, B., and Toulkeridis, T. (2022). Smart city planning based on landslide susceptibility mapping using fuzzy logic and multi-criteria evaluation techniques in the city of quito, ecuador. In *Doctoral Symposium on Information and Communication Technologies - DSICT*, pages 89–103.

Salehpour Jam, A., Mosaffaie, J., Sarfaraz, F., Shadfar, S., and Akhtari, R. (2021). Gis-based landslide susceptibility mapping using hybrid mcdm models. *Natural Hazards*, 108:1025–1046. Online:https://n9.cl/in8wa.

Secretaría Técnica de la Circunscripción Territorial Especial Amazónica (2021). *Plan Integral para la Amazonía 2021-203*. Secretaría Técnica de la Circunscripción Territorial Especial Amazónica.

Servicio Nacional de Gestión de Riesgos y Emergencias (2022a). Informe de situación no. 45 – época lluviosa a nivel nacional - cierre. Technical report, Servicio Nacional de Gestión de Riesgos y Emergencias.

Servicio Nacional de Gestión de Riesgos y Emergencias (2022b). Informe nro. 136 - época lluviosa del 01 de enero al 22 de julio de 2022. Technical report, Servicio Nacional de Gestión de Riesgos y Emergencias.

Soeters, R. and Van Westen, C. (1996). Slope instability recognition, analysis and zonation. *Landslides: investigation and mitigation*, 247:129–177. Online:https://n9.cl/vma1z.

Sonker, I., Tripathi, J., and Singh, A. (2021). Landslide susceptibility zonation using geospatial technique and analytical hierarchy process in sikkim himalaya. *Quaternary Science Advances*, 4:100039. Online:https://n9.cl/czyzla.

Tešić, D., Đorđević, J., Hölbling, D., Đorđević, T., Blagojević, D., Tomić, N., and Lukić, A. (2020). Landslide susceptibility mapping using ahp and gis weighted overlay method: a case study from ljig, serbia. *Serbian Journal of Geosciences*, 6(1):9–21. Online:https://n9.cl/h2k7n.

Van Westen, C. (1997). *ILWIS Applications Guide*, chapter Statistical landslide hazard analysis, pages 73–84. The International Institute for Aerospace Survey and Earth Sciences.

Varnes, D. and International Association of Engineering Geology (2021). *Landslide hazard zonation: a review of principles and practice*. Unesco.

Vásquez, J. y Estrada, M. (2023). A comparative study of the bivariate statistical methods and the analytical hierarchical process for the assessment of mass movement susceptibility. a case study: The lm-116 road-peru. *Rudarsko-geološko-naftni zbornik*, 38(1):149–166. Online:https://n9.cl/u17f0.

Wang, Z., Ma, C., Qiu, Y., Xiong, H., and Li, M. (2022). Refined zoning of landslide susceptibility: a case study in enshi county, hubei, china. *International journal of environmental research and public health*, 19(15):9412. Online:https://n9.cl/kwqq4.

Wieczorek, G. (1984). Preparing a detailed landslide-inventory map for hazard evaluation and reduction. *Bulletin of the Association of Engineering Geologists*, 21(3):337–342. Online:https://n9.cl/d0l2y.

Williams, C., Lee, S., Fisher, R., and Dickerman, L. (1999). A comparison of statistical methods

for prenatal screening for down syndrome. *Applied Stochastic Models in Business and Industry*, 15(2):89–101. Online:https://n9.cl/38to7.

Wubalem, A. and Meten, M. (2020). Landslide susceptibility mapping using information value and logistic regression models in goncha siso eneses area, northwestern ethiopia. *SN Applied Sciences*, 2:1–19. Online:https://n9.cl/pg3ik.

Zhou, S., Zhou, S., and Tan, X. (2020). Nationwide susceptibility mapping of landslides in kenya using the fuzzy analytic hierarchy process model. *Land*, 9(12):535. Online:https://n9.cl/a1cjp.

Zumpano, V., Paola, R., Balteanu, D., Hussin, H., Reichenbach, P., Bălteanu, D., Micu, M., and Sterlacchini, S. (2014). A landslide susceptibility analysis for buzau county, romania. *Rev. Roum. Géogr./Rom. Journ. Geogr*, 58(1):9–16. Online:https://n9.cl/ten7t.

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Veterinary Sciences

Molecular determination of the etiological agent of bovine mastitis from Andean production units

Determinación molecular del agente etiológico de la mastitis bovina de muestras provenientes de unidades productoras andinas

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Abstract

Bovine mastitis is a disease that affects the farms of small and medium producers in the cantons of Cayambe and Pedro Moncayo, Pichincha Province-Ecuador. Treating this disease is not easy due to the different microorganisms that cause it. This study focused on the molecular determination by means of polymerase chain reaction (PCR) of the etiological agents of mastitis, having multiple advantages when recognizing family, gender and species of microorganisms. It is a method capable of detecting resistance genes of antibiotics, an important analysis when diagnosing and treating diseases. The aim of this research is to identify bacteria causing bovine mastitis by using biochemical and molecular tests. Biochemical tests such as: Gram staining, Catalase, Coagulase, and Mannitol Salt Agar were efficient to obtain pure strains and determine the gender of some bacteria. Specific primers (RNA16S) were used for the molecular identification of 9 etiological agents causing the disease in the productive units. The microorganisms found were *Staphylococcus pasteuri, Staphylococcus warneri, Staphylococcus sp., Staphylococcus epidermidis, Staphylococcus aureus, Staphylococcus saprophyticus, Sphingomonas sp., Streptococcus dysgalactiae, Streptococcus uberis*, mostly present in clinic mastitis. To detect resistance genes, specific primers were used, of which 7 samples presented the gene for resistance to blaTEM (β-lactam) and 6 samples presented the gene for resistance to tetA (tetracyclines). Multi-resistance was identified in the species *Staphylococcus pasteuri, Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus uberis, Sphingomonas sp*.

Keywords: Mastitis, PCR, sequencing, biochemistry.

Resumen

La mastitis bovina es una enfermedad que afecta a las ganaderías de pequeños y medianos productores de los cantones Cayambe y Pedro Moncayo, Provincia de Pichincha-Ecuador. El tratamiento de esta enfermedad resulta complicado debido a la variedad de microorganismos que la provocan. El presente estudio se enfocó en la determinación molecular por medio de reacción en cadena de la polimerasa (PCR) de los agentes etiológicos de la mastitis. Esta técnica presenta múltiples ventajas al reconocer familia, género y especie de microorganismos, y es un método capaz de detectar genes de resistencia de antibióticos, lo que resulta importante al momento de diagnosticar y tratar enfermedades. El objetivo de esta investigación se centró en la identificación de bacterias causantes de la mastitis bovina, utilizando pruebas bioquímicas y moleculares. Las pruebas bioquímicas como tinción Gram, Catalasa, Coagulasa, y Agar Manitol Sal fueron eficientes para obtener cepas puras y determinar el género de algunas bacterias. Se utilizaron primers específicos (RNA16S) para la identificación molecular de 9 agentes etiológicos causantes de la enfermedad en las unidades productivas. Los microorganismos encontrados fueron; *Staphylococcus pasteuri, Staphylococcus warneri, Staphylococcus sp., Staphylococcus epidermidis, Staphylococcus aureus, Staphylococcus saprophyticus, Sphingomonas sp., Streptococcus dysgalactiae, Streptococcus uberis*, la mayoría presentes en mastitis clínica. Para detectar genes de resistencia se utilizaron primers específicos, de los cuales 7 muestras presentaron el gen para resistencia a blaTEM (β-lactámicos) y 6 muestras presentaron el gen para resistencia a tetA (tetraciclinas). Se identificó multirresistencia en las especies: *Staphylococcus pasteuri, Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus uberis, Sphingomonas sp*.

Palabras clave: Mastitis, PCR, secuenciación, bioquímica.

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1 Introduction

According to INEC and ESPAC (2016), 6,202,408 liters of milk are produced daily in Ecuador, in the Sierra region 4,810,551 liters (75% of national production), and in the province of Pichincha 873,272 liters. Torres (2018) estimates that Cayambe parish produces about 425,000 liters of milk daily, of which 51,000 liters are for consumption, 106,250 liters for artisanal production and 267,750 liters for bulk sale. Similarly, Céspedes Pachacama (2012), state that there is a daily milk production of 13,905 liters daily in Pedro Moncayo parish.

Bonifaz and Conlago (2016) state that mastitis causes great discomfort to farmers, causing a decrease in production and quality of milk, being affected in its chemical, physical and bacteriological composition, presenting a lower percentage of total solids, protein, fat and calcium. Mastitis is known as inflammation and irritation of the mammary gland caused by various pathogens, presenting increased somatic cells and causing discomfort in the animal; as a side effect of this infection, the texture of milk changes its organoleptic characteristics (Bhattarai et al., 2018).

According to Martínez (2012), the clinical symptoms are increased number of leukocytes, altered composition and appearance (lumps), fever, red, swollen and warm breast quarters. The occurrence of mastitis depends on the hygienic conditions of milking rooms (Zhang et al., 2018), age, breed, deliveries, lactation period, milk production and milking equipment conditions. If milking equipment is not used, the health and hygiene of the person in charge of milking the cows should be monitored (Gil Ruiz et al., 2016). Disease also occurs when environmental and animal management factors interact in such a way that the udder is exposed to pathogenic microorganisms. There are three essential factors that promote mastitis, the host, the infectious agent and the environment (Ruiz Gil et al., 2016).

Disease also occurs when environmental and animal management factors interact in such a way that the udder is exposed to pathogenic microorganisms. There are three essential factors that promote mastitis, the host, the infectious agent and the environment (Owens and Nickerson, 2011).

Studies have been conducted to identify the etiological agents that cause mastitis (Cervantes et al., 2017). The use of selective culture media has allowed isolate *Streptococcus agalactiae, Streptococcus uberis, Staphylococcus aureus, E. coli, Klebsiella, Pseudomona, Candida albicans* and *Proteus mirabilis*. Hernández et al. (2015) when identifying the etiological agents determined that *Staphylococcus aureus* is the most important microorganism with a 26% prevalence on the total of identified microorganisms in Boyacá parish.

The standard method for identifying pathogens consists of isolates in selective culture media, however, using this method will only be diagnosed up to the level of genus of the bacteria (Peña et al., 2012).

The prevalence of this disease in Cayambe and Pedro Moncayo is a problem, and the pathogenic microorganisms responsible continuously change their ecological dynamics by the mutations suffered by the etiological agents. For this reason, measures have been taken to identify the pathogens causing mastitis through biochemical tests and molecular techniques that allow establishing the pathogens and resistance to multiple antibiotics by their misuse when treating this disease (Bonifaz and Conlago, 2016).

Hence, the aim of this research is to determine by molecular techniques the etiological agents of bovine mastitis from samples coming from farms in Cayambe and Pedro Moncayo, as well as to identify the bacteria of the disease through 3 biochemical tests, to detect the resistance blaTEM genes for β-lactams and tetA for tetracyclines, in bacteria isolated in this research by PCR technique and finally to perform the molecular identification of the isolated microorganisms through sequencing of the ribosomal region RNA 16S.

2 Materials and methods

2.1 Milk sampling

Milk samples were taken from livestock farms located in Cayambe (coordinates 0°02′38″N 78°09′22″W) and Pedro Moncayo (coordinates 0°02′37″N 78°20′57″W) which had been previously identified as positive for mastitis by California Mastitis Test (CMT).

A total of 24 milk samples were collected following protocol LCL 001 of the milk quality laboratory of the Salesian Polytechnic University, which indicates that 40 mL of milk should be taken per container for its analysis in the FOSSOMATIC somatic cells (SCC) equipment by flow cytometry. Samples exceeding 500,000 CCS/dL as determined by Nieto et al. (2012) were selected for this study.

2.2 Microbial isolation

Milk samples were sown by swab in Triptein Soya Agar (TSA) medium, recommended for detecting and counting a wide range of bacteria, and incubation at 37°C for 48 hours (Britania Tripteína Soya Agar, 2015). Subsequently, several subcultures were performed to obtain pure colonies using the planting by exhaustion technique in TSA medium (Milián et al., 2014). Pure bacterial colonies were confirmed by Gram stain.

2.3 Identification by biochemical tests

Four biochemical tests of bacterial identification were performed: Gram stain to differentiate bacilli and cocci Gram (+) and Gram (-); Catalase using 30% hydrogen peroxide expecting to visualize presence or absence of bubbling (Wanger et al., 2017); Coagulase test in human plasma, where pure strains and incubated at 37°C for 24 hours were inoculated to analyze presence or absence of coagulation (American Society for Microbiology, 2016); and Agar Mannitol Salt (AMS) where sowing of strains were performed, isolated and incubated at 37°C for 48 hours in order to differentiate bacteria of the genus *Staphylococcus* (Vila et al., 2004). The purpose of these tests was to prevent molecular analyzes from being performed on repeated bacterial species.

2.4 DNA extraction and 16S rRNA amplification

The pure strains were massified in Tryptic Soya Broth (TSB) medium until reaching a concentration of 12×10^8 (CFU/mL) which was determined by comparison with turbidity patterns of the McFarland scale. In 1.5 mL tubes, 1 mL of bacterial culture of each massified strain was placed and the sample was centrifuged to form a pellet of bacteria that was used for DNA extraction based on Becton et al. (2005). Total DNA extraction was performed using the Köchl et al. (2005) DNA extraction protocol. The presence or absence of DNA was confirmed by 1% agarose gel electrophoresis (González de Buitrago, 2010). The DNA obtained was preserved in a solution of Tris-EDTA at -20°C (Tan and Yiap, 2009).

The amplification of the 16S rRNA region was performed using the first 27F (5′TCCTACGGGAGGCAGCAGT3′) and 1492R (5′GGACTACCAGGGTATCTAATCCTGTT3′) designed by Marchesi et al. (1998). The PCR technique and Labnet Multigene branded thermo-cycler were used under the following conditions: initial denaturation at 95°C for 5 minutes, 25 denaturation cycles at 95°C for 1 minute, annealing at 60°C for 2 minutes, initial extension for 1 minute at 72°C and final extension for 7 minutes at 72°C followed by maintenance at 4°C (Kang et al., 2015). The presence of amplicons was determined by 1% agarose gel electrophoresis.

2.5 Sequencing and sequence analysis

Amplicons were sequenced using the Sanger technique in MACROGEN, South Korea. The sequences obtained were compared with existing sequences in the GeneBank of the National Center for Biotechnological Information (NCBI). Subsequently, the sequences were aligned with the Muscle software tool Mega 6 to obtain a phylogenetic tree using the *neighbor joining* tool of Mega 6 to make a correct taxonomic classification of the isolated etiological agents (Fuertes and Cerna, 2018).

2.6 Antibiotic resistance gene amplification blaTEM (β-lactam) and tatA (tetracycline)

The presence or absence of antibiotic resistance genes was determined using the following specific primers described by Tao et al. (2014), for blaTEM: Forward (5′GCA CGA GTG GGT TAC ATC GA 3′) and Reverse (5′GGT CCT CCG ATC GTT GTC AG 3′). The approximate size of the resistance gene is 300 bp; for tetA: Forward (5′GCT ACA TCC TGC TTG CCT TC 3′) and Reverse (5′CAT AGA TCG CCG TGA GG 3′). According to Belding and Boopathy (2018), the approximate size of the resistance

gene is between 250 and 300 bp. The results obtained were verified in 1% agarose gel electrophoresis.

3 Results and discussion

3.1 Identification by biochemical tests

A total of 17 bacterial strains were isolated. The Gram stain resulted in 15 Gram-positive and 2 Gram-negative species as shown in Table 1.

After having applied catalase tests, 11 catalase positive and 6 catalase negative species were identified. Coagulase tests identified 1 coagulase-positive species and 16 coagulase-negative species. Chaneton (2010) states that coagulase negative *Staphylococcus* are the most prevalent pathogens, being identified according to the type of infection 47% in latent infection and 28% in subclinical mastitis.

Planting Agar Mannitol Salt (AMS) allowed to classify 4 species as positive to mannitol fermentation, 8 species negative to mannitol fermentation and 5 bacterial species that did not give a determined result.

Table 1. Results obtained from the Biochemical tests.

Code of the sample	Application of Biochemical tests			
	Gram Staining	Catalase	Coagulase	Agar Mannitol Sal
835	+	+	-	+
A2r	+	+	-	+
D2r	+	+	-	****
I2r	+	+	-	+
A3r	+	+	-	+
809	+	+	-	-
798	+	+	+	****
799c1	+	+	-	-
H3R	+	+	-	-
11	+	-	-	****
11^a	+	-	-	****
1C	-	+	-	-
2C	-	+	-	****
1B	+	-	-	-
E1	+	-	-	-
99	+	-	-	-
799	+	-	-	-

Classification result by biochemical tests of bacterial isolates; (+) = Positive result, (-) = Negative result, (****) = Unfinished result.

3.2 Identification by molecular methods

The total DNA obtained was approximately 7000 bp, based on the molecular classification of the Thermo Scientific 2× Phire Plant Direct kit (Figure 1).

Amplification of the 16S rRNA region resulted in bands of approximately 1300 bp (Figures 2 and 3). The validity of the obtained sequences was analyzed using FinchTV software, which discarded 3 sequences due to lack of adequate quality. With the remaining sequences the identity of 15 species corresponding to the Bacteria domain was obtained.

The sequences obtained in this research were compared with sequences present in the database at the NCBI GeneBank. The identity percentages exceeded 97% in all cases except for strains coded as 1C, 2C and E1. Sol-Church and Frenck (2014), suggest accepting identity percentages higher than 95%. Sequences of the species cataloged as D2r, 798 and 2C did not have a taxonomic record in the NCBI database being cataloged as non-cultured bacteria.

To make a correct identification of the isolated etiological agents, a phylogenetic tree was developed using the 15 obtained sequences and 4 external reference sequences downloaded from the NCBI database (Figure 4).

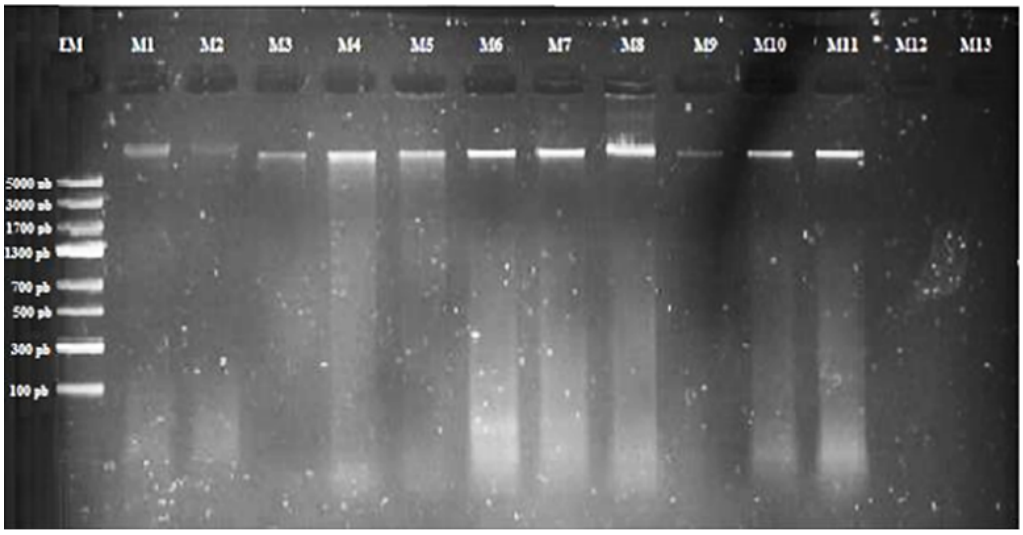

Figure 1. Total DNA in electrophoresis gel.

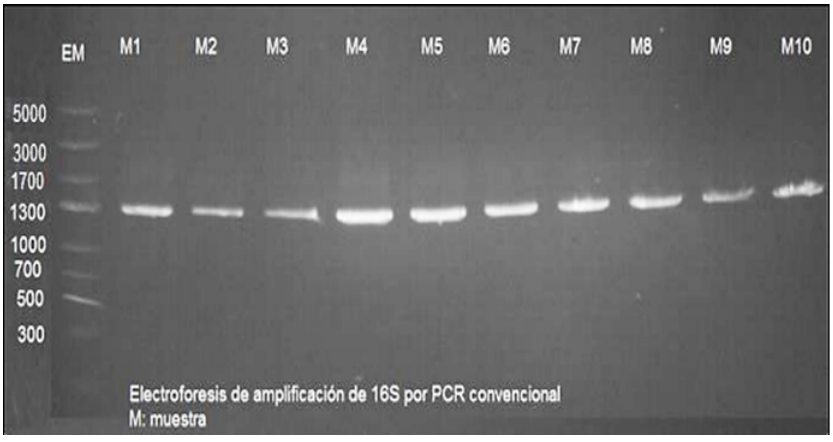

Figure 2. Amplification of 16S electrophoresis by conventional PCR.

Isolated species were identified as etiological agents causing mastitis in dairy cattle in the study area. Based on the information obtained with the phylogenetic tree, three clades were established:

- Clade (I): The isolates identified as *Staphylococcus* sp. (A3r), emphS. pasteuri (835, A2r), *S. Warneri* (I2r), *S. epidermidis* (809) and *S. saprophyticus* (799c1), are found in this clade. There were species that could not be identified at taxonomic level as is the case of Bacterium strain 2BL_4 (D2r) which was aligned with *S. warneri* and an uncultured bacteria clone ncd2254e01c2 (798), species that were grouped to the reference sequence of *Staphylococcus aureus*, used as external species, determining that these may belong to the same genus but with a different strain.

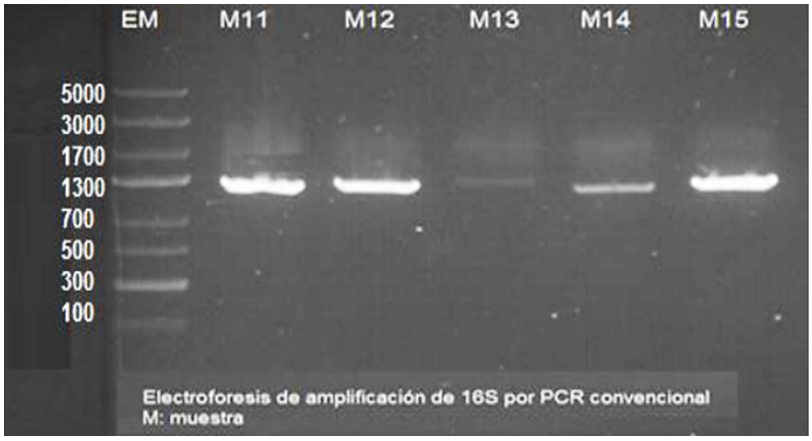

Figure 3. Amplification of 16S electrophoresis by conventional PCR.

- Clade (II): They include *Sphingomonas* sp. (C1) and Bacterium strain 4BL_5 (2C) closely grouped with the reference strain type of ATCC *Sphingomonas paucimobilis*, relationship confirmed by Clavijo et al. (2012), since there are genera that are within the same group, share characteristics and also coincide with molecular identification.

- Clade (III): All isolates in clade III coincide to be of the same *Streptococcus* genus when grouped in the following species *S. uberis* (99, 799), *S. dysgalactiae* (B1) which was grouped with *Streptococcus* sp. (E1).

In Table 2, the genera of pathogens identified in this research are *Staphylococcus, Sphingomonas* and *Streptococcus*. Bacteria including *Sphingomonas* and *Streptococcus* bacteria are normal components of skin microbiota (Chen et al., 2018).

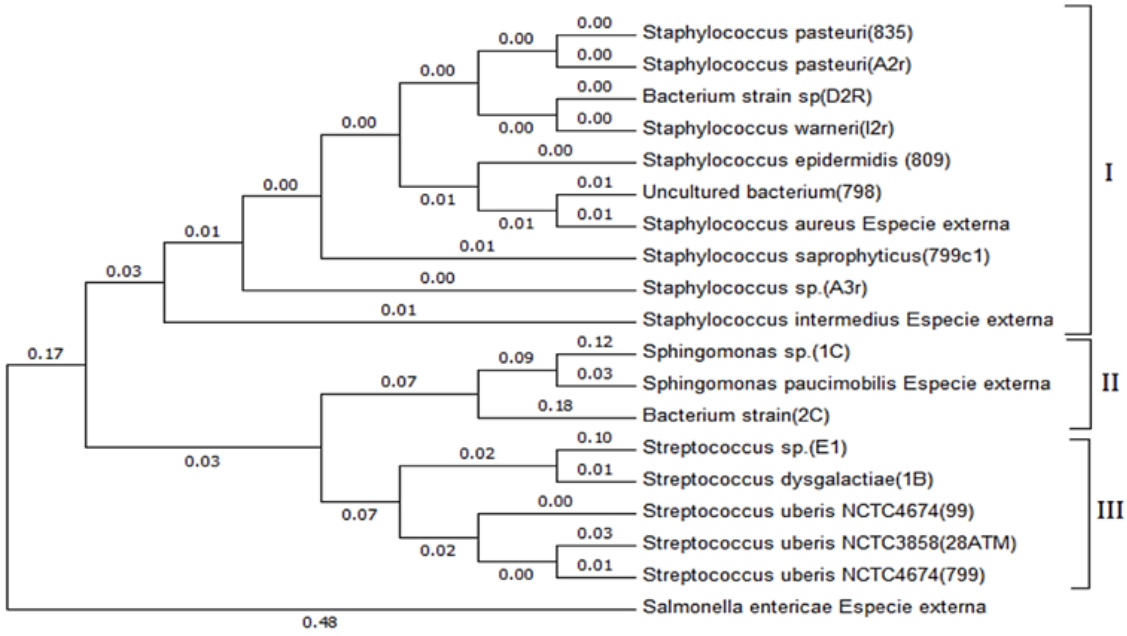

Figure 4. Phylogenetic tree elaborated from the sequencing of the 16S rRNA region of the isolated species.

According to Fariña et al. (2013), *Sthaphylococcus* is one of the most frequently isolated genera in mastitis prevalence studies. Lange et al. (2015) say that species belonging to the *Streptococcus* genus are linked to bovine mastitis as opportunistic bacteria. Ruiz et al. (2011) in their study on subclinical mastitis associated with manual and mechanical milking. *Staphylococcus* sp. is the main pathogen with 61% predominance followed by *Streptococcus* sp. with 29.6% incidence. Braga et al. (2018) when performing an identification of bovine mastitis pathogens by MALDI-TOF mass spectrophotometry determined that approximately 80% of the cases of mastitis were caused by the group of bacteria *Staphylococcus aureus, Streptococcus uberis* and *Streptococcus dysgalactiae*.

Table 2. Taxonomic classification of etiological agents causing bovine mastitis isolated in Cayambe and Pedro Moncayo, Pichincha province.

Code	Species	Query cover (%)	Identity	Access
835	*Staphylococcus pasteuri*	99	97	gi|388894673|JQ726643.1
A2r	*Staphylococcus pasteuri*	100	99	gi|762210140|LN623633.1
D2r	*Staphylococcus* sp.	98	99	gi|1193828147|MF112182.1
I2r	*Staphylococcus warneri*	99	99	gi|1409189597|MF662223.1
A3r	*Staphylococcus* sp. *strain CLC-F26*	100	99	gi|1408623646|MH518208.1
809	*Staphylococcus epidermidis strain TWSL_20*	96	99	gi|846351151|KT184900.1
798	*Staphylococcus* sp.	91	98	gi|322180115|JF194710.1
799c1	*Staphylococcus saprophyticus strain WWi167*	99	99	gi|1393269660|MH396756.1
1C	*Sphingomonas* sp. *strain Ap02E*	78	89	gi|1080032407|KX990222.1
2C	*Sphingomonas* sp.	97	91	gi|1193828182|MF112217.1
1B	*Streptococcus dysgalactiae strain JZ R-75*	34	99	MH119693.1
E1	*Streptococcus* sp. *XJ150-1212-NJR1*	95	90	gi|564983989|KF828882.1
99	*Streptococcus uberis strain NCTC4674*	99	99	gi|1403452574|LS483408.1
799	*Streptococcus uberis strain NCTC3858*	99	97	gi|1403426722|LS483397.1

Source: NCBI(2019).

Davies et al. (2016) mention that 63% of potential transmission events and 38% of incidence of clinical mastitis are caused by *S. uberis* in dairy herds. Nam et al. (2009) mention that about 40% of clinical mastitis cases are caused by Gram (-) bacteria linked to mastitis, the most common non-coliform pathogen associated with intramammary infections is *Sphingomonas* sp.

3.3 Antibiotic resistance assay

Amplification of the blaTEM resistance gene for the β-lactam family resulted in bands of approximately 300 bp, data corroborated by Tao et al. (2014). The

resistance gene was found in *Staphylococcus pasteuri, Staphylococcus warneri, Staphylococcus epidermidis, Staphylococcus saprophyticus, Streptococcus uberis, Sphingomonas* sp. and *Staphylococcus aureus* species (Figure 5).

On the other hand, amplification of the tetA resistance gene for the tetracycline family resulted in bands of approximately 250 bp. According to Belding and Boopathy (2018), the resistance gene for the tetracycline antibiotic family has a size of between 210 and 300 bp. The resistance gene was found in *Staphylococcus pasteuri, Staphylococcus epidermidis, Streptococcus uberis, Streptococcus dysgalactiae, Staphylococcus aureus* and *Sphingomonas* sp. (Figure 6).

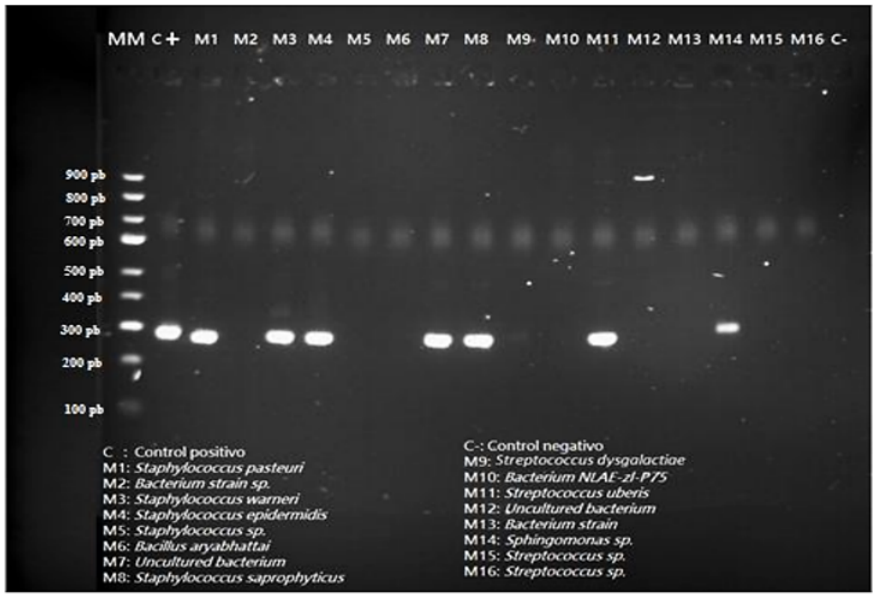

Figure 5. Electrophoresis gel showing presence/absence of blaTEM resistance gene for β-lactam antibiotics.

Corroborating the results obtained in this study (Table 3), further antibiotic resistance studies in mastitis-related pathogens have determined that β-lactam-resistant species are *Staphylococcus warneri, Streptococcus uberis* (Bonetto, 2014), *Staphylococcus epidermidis* (Fariña et al., 2013), *Staphylococcus saprophyticus, Sphingomonas* sp., *S. aureus* (Ramírez et al., 2018) and *Staphylococcus pasteuri* (Arrepia, 2008). Likewise, according to studies carried out by other authors, *S. epidermidis* (Ramírez et al., 2018), *S. uberis, S. dysgalactiae* (Florentin, 2007) and *S. pasteuri* (Savini et al., 2009) have resistance to tetracyclines, the latter showing resistance to different antibiotic compounds such as methicillin/ oxacillin, macrolides, lincosamides, streptogramins and tetracyclines.

Table 3. Species resistant to β-lactam and tetracyclines.

Species with blaTEM resistance	Species with tetA resistance
Staphylococcus pasteuri	*Staphylococcus pasteuri*
Staphylococcus aureus	*Staphylococcus aureus*
Staphylococcus epidermidis	*Staphylococcus epidermidis*
Streptococcus uberis	*Streptococcus uberis*
Sphingomonas sp.	*Sphingomonas* sp.
Staphylococcus warneri	*Streptococcus dysgalactiae*
Staphylococcus saprophyticus	

4 Conclusions

The use of the molecular technique allowed to identify genus and species in most of the isolated microorganisms, concluding that the molecular identification of the etiological agent is important in the study of bovine mastitis as it is a more specific test

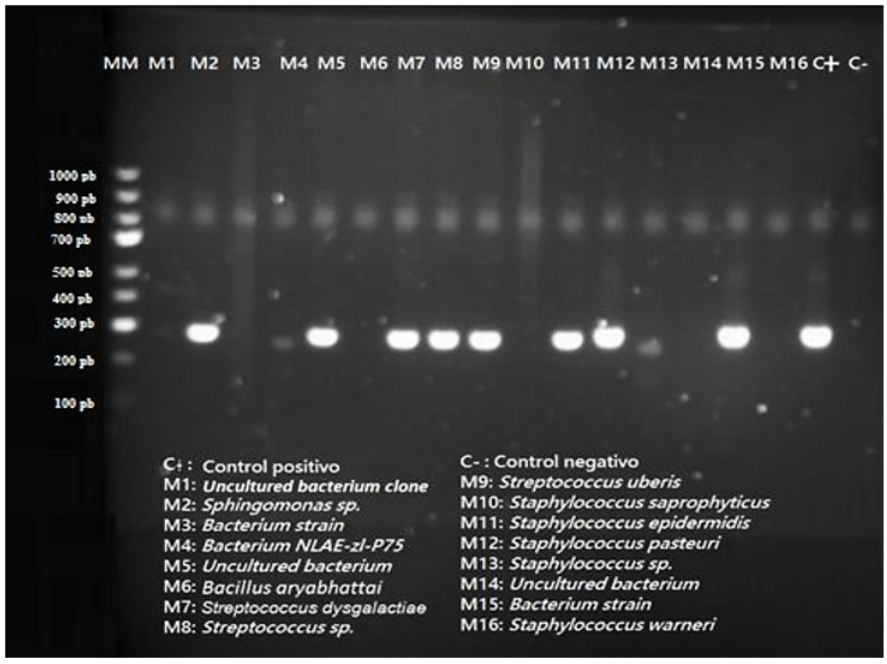

Figure 6. Electrophoresis gel showing presence/absence of tetA resistance gene for antibiotics of the tetracycline family.

than biochemical.

It could be determined that the etiological agents with more prevalence of bovine mastitis in Cayambe and Pedro Moncayo are the microorganisms belonging to the genera *Staphylococcus* and *Streptococcus*, being the most common *Staphylococcus pasteuri, Staphylococcus warneri, Staphylococcus* sp., *Staphylococcus epidermidis, Staphylococcus aureus, Staphylococcus saprophyticus, Sphingomonas* sp., *Streptococcus dysgalactiae, Streptococcus uberis*.

The molecular technique also allowed to identify in the bacteria causing bovine mastitis the presence of resistance genes to two families of antibiotics. The bacteria resistant to β-lactam were *Staphylococcus pasteuri, Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus uberis* and *Sphingomonas* sp; and bacteria determined as resistant to tetracyclines were *Staphylococcus pasteuri, Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus uberis, Sphingomonas* sp., *Streptococcus dysgalactiae*.

The molecular identification of different genera and bacterial species that cause bovine mastitis together with the study of antibiotic resistance genes allows a safer diagnosis to establish an effective treatment against this multifactorial disease that affect lactating cows in most dairy production units in Ecuador.

Author Contributions

NFBG; Conceptualization, Project Administration, Research methodology, Responsibility, Visualization, Original draft writing, review and editing. XAGJ; Methodology, field and laboratory research, milk sampling, microbiology, data processing at the molecular level. BGFF; Methodology, laboratory research, microbiology data processing at the molecular level. NJBG; Conceptualization, data processing, formal analysis, data curation.

References

American Society for Microbiology (2016). Coagulase test protocol. Online:https://bit.ly/3GVDLqd.

Arrepia, E. (2008). Prevalência da resistência a antibióticos, metais e desinfectantes em isolados de *Staphylococcus* provenientes de uma etar munici-

pal. Master's thesis, Universidade do Porto. Online:https://bit.ly/3BfsHRv.

Belding, C. and Boopathy, R. (2018). Presence of antibiotic-resistant bacteria and antibiotic resistance genes in coastal recreational waters of southeast louisiana, usa. *Journal of Water Supply: Research and Technology-AQUA*, 67(8):800–809. Online:https://bit.ly/41eBvT8.

Bhattarai, D., Worku, T., Dad, R., Rehman, Z., Gong, X., and Zhang, S. (2018). Mechanism of pattern recognition receptors (prrs) and host pathogen interplay in bovine mastitis. *Microbial Pathogenesis*, 120:64–70. Online:https://bit.ly/3mN7bAc.

Bonetto, C. (2014). *Mastitis bovina causada por* Staphylococcus *coagulasa negativos. Retrieved from degree Thesis information Doctor en Ciencias Veterinarias, Universidad Nacional de la Plata.* PhD thesis, Universidad Nacional de La Plata. Online:https://bit.ly/3px3qQ8.

Bonifaz, N. and Conlago, F. (2016). Prevalencia e incidencia de mastitis bovina mediante la prueba decalifornia mastitis test con identificación del agente etiológico, en paquiestancia, ecuador. *La Granja*, 24(2):43–52. Online:https://bit.ly/3KLBbnN.

Braga, P., Gonçalves, J., Barreiro, J., Ferreira, C., Tomazi, T., Eberlin, M., and Santos, M. (2018). Rapid identification of bovine mastitis pathogens by maldi-tof mass spectrometry. *Pesquisa Veterinária Brasileira*, 38:586–594. Online:https://bit.ly/42OddzT.

Britania Tripteína Soya Agar (2015). *Manual uso de Tripteína Soya Agar, Britanialab.com*. Online:https://bit.ly/40D0Q82.

Cervantes, P., Portela, S., Hernández, A., Domínguez, B., Gómez-Boucrin, F., Villagómez-Cortes, J., and Barrientos, M. (2017). Aislamiento de patógenos causantes de mastitis subclínica en vacas del trópico húmedo en veracruz, méxico. *Actas Iberoamericanas en Conservación Animal AICA*, 10:103–109. Online:https://bit.ly/41gDYwk.

Chaneton, L. (2010). *Nuevos enfoques en el diagnóstico, prevención y tratamiento de la mastitis bovina a través del uso de moléculas con acción antimicrobiana*. PhD thesis, Universidad de Buenos Aires. Online:https://bit.ly/3HUP56I.

Chen, Y., Fischbach, M., and Belkaid, Y. (2018). Skin microbiota-host interactions. *Nature*, 553:427–436. Online:https://go.nature.com/3KOmm3R.

Clavijo, C., Chipana, V., Centeno, J., Zúñiga, D., and Guillén, C. (2012). Aislamiento, caracterización e identificación de bacterias diazotróficas de la rizósfera del cultivo de *Olea europea* "olivo" en tacna perú. *Ecología Aplicada*, 11(2):89–102. Online:https://n9.cl/5bpg0.

Davies, P., Leigh, J., Bradley, A., Archer, S., Emes, R., and Green, M. (2016). Molecular epidemiology of *Streptococcus uberis* clinical mastitis in dairy herds: strain heterogeneity and transmission. *Journal of Clinical Microbiology*, 54(1):68–74. Online:https://bit.ly/41nnClL.

Fariña, N., Carpinelli, L., Samudio, M., Guillén, R., Laspina, F., Sanabria, R., Abente, S., Rodas, L., Gonzalez, P., and de Kaspar, H. (2013). Clinically significant coagulase-negative staphylococci: most frequent species and virulence factors. *Revista Chilena de Infectología: Órgano Oficial de La Sociedad Chilena de Infectología*, 30(5):480–488. Online:https://bit.ly/3Ackehp.

Florentin, C. C. (2007). Perfil de resistencia *In Vitro* a antimicrobianos de cepas causantes de mastitis aisladas de leche cruda bovina en establecimientos de pequeña y mediana producción. *Memorias del Instituto de Investigaciones en Ciencias de la Salud*, 5(1):19–25. Online:https://bit.ly/3ULnIkw.

Fuertes, G. and Cerna, M. (2018). Identificación morfológica y molecular de hongos micorrízicos de especies del género *Dracula y Epidendrum (Orchidaceae)*. volume 1 of *Bionatura Conference Serie*, pages 1–17. Online:https://bit.ly/3pkzYwI.

González de Buitrago, J. (2010). *Técnicas y Métodos de Laboratorio Clínico*, chapter 15 - Electroforesis, page 211–217. Online:https://bit.ly/3plSRzk. Elsevier España.

Hernández, J., Angarita, M., Benavides, D., and Prada, C. (2015). Agentes etiológicos de mastitis bovina en municipios con importante producción lechera del departamento de boyacá. *Revista Investigación en Salud Universidad de Boyacá*, 2(2):162–176. Online:https://bit.ly/3on9uu5.

INEC and ESPAC (2016). Encuesta de superficie y producción agropecuaria continua espac

2016. Technical report. Online:https://bit.ly/3UQDYRm.

Kang, J., Noh, E., Park, J., An, C., Choi, J., and Kim, J. (2015). Rapid origin determination of the northern mauxia shrimp (*Acetes chinensis*) based on allele specific polymerase chain reaction of partial mitochondrial 16s rrna gene. *Asian-Australasian Journal of Animal Sciences*, 28(4):568–572. Online:https://bit.ly/3MT8IiJ.

Köchl, S., Niederstätter, H., and Parson, W. (2005). *Forensic DNA typing protocols*, volume 297, chapter DNA extraction and quantitation of forensic samples using the phenol-chloroform method and real-time PCR, pages 13–29. Online:https://bit.ly/41s672W. Humana Press.

Lange, C., Brito, M., Reis, D., Machado, M., Guimaraes, A., Azevedo, A., Salles, E., Alvim, M., Silva, F., and Meurer, I. (2015). Species-level identification of staphylococci isolated from bovine mastitis in brazil using partial 16s rrna sequencing. *Veterinary Microbiology*, 176(3-4):382–388. Online:https://bit.ly/41r7gbG.

Marchesi, J., Sato, T., Weightman, A., Martin, T., Fry, J., Hiom, S., and Wade, W. (1998). Design and evaluation of useful bacterium-specific pcr primers that amplify genes coding for bacterial 16s rrna. *Applied and Environmental Microbiology*, 64(2):795–799. Online:https://bit.ly/41K8rmZ.

Martínez, G. (2012). Prácticas de ordeño y prevalencia de mastitis subclínica en vacas lecheras que abastecen el centro de acopio uldesa del municipio el sauce en el departamento de león septiembre-noviembre 2011. Master's thesis, Universidad Nacional Autónoma de Nicaragua. Online:https://bit.ly/44SdZxI.

Milián, G., Rondón, A., Pérez, M., Samaniego, L., Riaño, J., Bocourt, R., Ranilla, M., Carro, M., and Rodríguez, M. (2014). Aislamiento e identificación de cepas de *Bacillus spp*. en diferentes ecosistemas con fines probióticos. su utilización en animales. *Revista Cubana de Ciencia Agrícola*, 48(4):347–351. Online:https://bit.ly/3AkYb8l.

Nam, H., Lim, S., Kang, H., Kim, J., Moon, J., Jang, K., Joo, Y., and Jung, S. (2009). Prevalence and antimicrobial susceptibility of gram-negative bacteria isolated from bovine mastitis between 2003 and 2008 in korea. *Journal of Dairy Science*, 92(5):2020–2026. Online:https://bit.ly/3UXqRhi.

Nieto, D., Berisso, R., Demarchi, O., and Scala, E. (2012). Manual de buenas prácticas de ganadería bovina para la agricultura familiar: Tratamientos bovinos. ministerio de ganadería, chile. Technical report. Online:https://www.fao.org/3/i3055s/i3055s.pdf.

Owens, W. and Nickerson, S. (2011). *Mastitis Therapy and Control | Medical Therapy Options*, chapter Encyclopedia of Dairy Sciences(Second Edition), page 435–439. Online:https://bit.ly/3nPL5xq. Elsevier.

Peña, W., Morillo, S., Sosa, M., Morales, J., Cañizalez, L., and Castillo, C. (2012). Identificación de bacterias causantes de mastitis subclínica en bovinos de una finca del estado trujillo-venezuela. *Revista Academia*, 11(24):355–363. Online:https://bit.ly/3MZIBXr.

Ramírez, N., Fernández, J., and Palacio, L. (2018). Taxa de incidência de mastite clínica e susceptibilidade antibiótica de patógenos produtores de mastite em gado leiteiro do norte de antioquia, colômbia. *Revista de Medicina Veterinaria*, (36):75–87. Online:https://n9.cl/aq2ze.

Ruiz, A., Ponce, P., Gomes, G., Mota, R., Elizabeth, S., Lucena, E., and Benone, S. (2011). Prevalencia de mastitis bovina subclínica y microorganismos asociados: comparación entre ordeño manual y mecánico, en pernambuco, brasil. *Revista de Salud Animal*, 33(1):57–64. Online:https://n9.cl/n45jo.

Ruiz Gil, A., Peña Rodríguez, J., and Remón Díaz, D. (2016). Mastitis bovina en cuba. artículo de revisión. *Revista de Producción Animal*, 28(2-3):39–50. Online:https://bit.ly/420v6v1.

Savini, V., Catavitello, C., Bianco, A., Balbinot, A., and D'Antonio, D. (2009). Epidemiology, pathogenicity and emerging resistances in staphylococcus pasteuri: from mammals and lampreys, to man. *Recent Patents on Anti-Infective Drug Discovery*, 4(2):123–129. Online:https://bit.ly/3V4ley0.

Sol-Church, K. and Frenck, J. (2014). Sequencing guidelines. biomolecular core facility. Technical report. Online:https://bit.ly/3AoZW4n.

Tan, S. and Yiap, B. (2009). Dna, rna, and protein extraction: the past and the present. *Journal of Biomedicine and Biotechnology*, 2009(574398. Online:https://bit.ly/3AkdwpL).

Tao, C.-W., Hsu, B.-M., Ji, W.-T., Hsu, T.-K., Kao, P.-M., Hsu, C.-P., Shen, S.-M., Shen, T.-Y., Wan, T.-J., and Huang, Y.-L. (2014). Evaluation of five antibiotic resistance genes in wastewater treatment systems of swine farms by real-time pcr. *Science of the Total Environment*, 496:116–121. Online:https://bit.ly/40vEDIY.

Torres, X. (2018). Estudio de la producción de la industria láctea del cantón cayambe en el período 2009-2015. Master's thesis, Universidad Andina Simón Bolívar, Sede Ecuador. Online:https://bit.ly/3NZDA1I.

Vila, A., Zhurbenko, R., and Viera, D. (2004). Propuesta de una modificación en la formulación del medio agar manitol salado utilizado en el aislamiento de estafilococos de importancia clínica. *Revista Cubana de Medicina Tropical*, 56(3):172–177. Online:https://n9.cl/60tsu.

Wanger, A., Chavez, V., Huang, R., Wahed, A., Actor, J., and Dasgupta, A. (2017). *Microbiology and Molecular Diagnosis in Pathology*, chapter Chapter 5 - Biochemical Tests and Staining Techniques for Microbial Identification, page 61–73. Online:https://bit.ly/3nQxKVy. Elsevier.

Zhang, S., Piepers, S., Shan, R., Cai, L., Mao, S., Zou, J., Ali, T., De Vliegher, S., and Han, B. (2018). Phenotypic and genotypic characterization of antimicrobial resistance profiles in *Streptococcus dysgalactiae* isolated from bovine clinical mastitis in 5 provinces of china. *Journal of Dairy Science*, 101(4):3344–3355. Online:https://bit.ly/43Wgw9g.

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Scientific paper/ Artículo científico

Biotechnology

Response of flour corn (*Zea mays L. var. Amylacea*) to the inoculation of *Azospirillum* and *Pseudomonas*

Respuesta del maíz harinoso (*Zea mays L. var. Amylacea*) a la inoculación de *Azospirillum* y *Pseudomonas*

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Abstract

Plant growth-promoting bacteria (PGPB) that inhabit root rhizosphere of plants are of great agricultural importance due to their ability to produce phytohormones during root colonization. These phytohormones produce physiological changes in the plant that favor a greater absorption of nutrients, promote growth and increase production. This study analyzed the effect of inoculation of two of these bacteria, *Azospirillum* sp. and *Pseudomonas fluorescens*, under field conditions representative of the Andean Highlands. The experiment was carried out using flour corn seed of the INIAP-101 variety in a randomized complete block design with six repetitions. The treatments corresponded to: T1 (*Azospirillum* sp.), T2 (*P. fluorescens*), T3 (*Azospirillum* sp. and *P. fluorescens*), T4 (control, conventional chemical fertilization) and T5 (absolute control). The application of these bacteria significantly increased ($p<0.05$) the root length, the diameter of the cob, and the yield of fresh corn ("elotes" or "choclos"). The combined inoculation of these bacteria (T3) obtained the highest yield, with 19.70 t ha^{-1} of fresh corn; while the chemical control and the absolute control got 17.12 and 13.58 t ha^{-1} of fresh corn, respectively. The economic analysis of T3 reported a benefit/cost of 1.35, which indicates that the synergism of these two bacteria could be a sustainable strategy to improve yields and reduce the use of chemical fertilizers for corn production in the Andean region.

Keywords: biofertilizers, bioinoculants, fresh corn, sustainable production.

Resumen

Las bacterias benéficas que habitan la rizósfera de las plantas son de gran interés agrícola debido a su capacidad para producir fitohormonas durante la colonización radicular. Estas fitohormonas producen cambios fisiológicos en la planta que favorecen una mayor absorción de nutrientes que provocan un rápido crecimiento vegetativo y una mayor producción. Esta investigación tuvo como objetivo evaluar el efecto de la inoculación de dos de estas bacterias, *Azospirillum* sp. y *Pseudomonas fluorescens* en el cultivo de maíz harinoso bajo condiciones de campo típicas de la región alto andina. El experimento se realizó utilizando semilla de maíz harinoso de la variedad INIAP-101 con un diseño de bloques completos al azar y seis repeticiones. Los tratamientos correspondieron a: T1 (*Azospirillum* sp.), T2 (*P. fluorescens*), T3 (*Azospirillum* sp. y *P. fluorescens*), T4 (testigo con fertilización química convencional) y T5 (testigo absoluto). La aplicación de estas bacterias incrementó de manera significativa ($p<0,05$) la longitud de raíz, el diámetro de la mazorca y el rendimiento del maíz tierno (elotes o choclos). La inoculación combinada de estas bacterias (T3) obtuvo el mayor rendimiento con 19,70 t ha^{-1} de choclos, mientras que el testigo químico y el testigo absoluto obtuvieron 17,12 y 13,58 t ha^{-1} de choclos, respectivamente. El análisis económico de T3 reportó un coste/beneficio de 1,35, lo cual indicó que el sinergismo de estos dos géneros podría ser una estrategia sostenible para mejorar los rendimientos y reducir el uso de fertilizantes químicos en el cultivo de maíz de la región Andina.

Palabras clave: biofertilizantes, bioinoculantes, choclo, producción sustentable.

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1 Introduction

Flour corn (*Zea mays* L. var. *Amylacea*) is one of the most important crops in the Ecuadorian Highlands, due to the large amount of land used for its production and the role it plays as a basic component of the population's diet (Yánez et al., 2013). Around 62 581 ha of this cereal are grown annually, doubling the area planted with other important crops in the highlands such as potato, bean, wheat, and barley (Continuous Agricultural Production and Area Survey (ESPAC; by its acronym in Spanish) (ESPAC, 2018). Unfortunately, the yield of this type of corn reaches up to 0.93 t ha^{-1} for dry grain, and 3.75 t ha^{-1} for fresh corn, placing Ecuador among the lowest flour corn productivity levels in South America (Boada and Espinosa, 2016).

Flour corn is usually planted in small lots up to one hectare, and a large proportion of these lots are located on marginal soils that include hillside areas, with soils exposed to erosion and no irrigation facilities. In addition, most of the farmers use uncertified seeds and unimproved native varieties. All these, and other socioeconomic factors make corn yield very low, which limits farmer´s purchasing power and restricts the use of inputs, such as fertilizers.

The yield of corn is closely related to the availability of soil nutrients. For corn grown in the highlands, it is recommended to apply 80 kg ha^{-1} of nitrogen and 40 kg ha^{-1} of phosphorous in soils of intermediate fertility (Yánez et al., 2013). After nitrogen, phosphorus is one of the most important elements in the early stages of normal plant development; a deficiency of these elements in the crop can cause slow growth, little development of the root system and therefore reduces the yield of the harvest (Guzmán, 2012). Plant growth-promoting bacteria (PGPB) facilitates plant growth by providing either fixed nitrogen or phosphorus and induces the production of phytohormones during root colonization. These phytohormones produce physiological changes in the plant that favor a greater absorption of nutrients, promote growth, and increase production (Glick, 2012; Santoyo et al., 2016).

Currently, it is pivotal to investigate the soil microbiota to obtain strategies that improve agricultural productivity. One of these strategies is the application of bioinoculants with beneficial microorganisms which, applied to the soil or the seed, generate a positive impact on plant nutrition and yield (Glick, 2012; Díaz-Blanco and Márquez-Reina, 2011). The use of bioinoculants made from beneficial microorganisms, such as *Azospirillum* sp. and *Pseudomonas fluorescens*, that live associated or in symbiosis with the roots of corn, can efficiently contribute to nitrogen fixation, phosphorus solubilization, and natural soil fertility, providing a positive agrobiological effect that constitutes an important alternative for the reduction or partial substitution of mineral fertilizers (Grageda et al., 2012; Pereira et al., 2020).

The study and management of beneficial microorganisms has increased to such a degree that nowadays a whole commercial movement has been generated. The production and commercialization of bioinoculants are aimed to strength a sustainable production system with an ecological balance of the soil (Ruiz, 2015; Urrutia, 2019). Several studies have shown the benefits of the use of bioinoculants or biofertilizers in dent and flint corn in lowlands, increasing yield and cost effectiveness for farmers, but reports on flour corn in the highlands are scarce. In Mexico, García et al. (2012) showed that the inoculation with *A. brasilense* increased grain yield compared with the non-fertilized and non-inoculated control, increasing the benefit/cost by 56% on average. Later,Martínez-Reyes et al. (2018) reported that the use of a biofertilizer with *A. brasilense* increased the yield of grain up to 28.0% (1.67 t ha^{-1}) with respect to the absolute control, achieving a greater net benefit than the use of conventional chemical fertilization. In Brazil, Pereira et al. (2020) reported that the use of bioinoculants increased grain yield up to 39.5 and 34.7% when corn seed was inoculated with *Bacillus subtillis* and *A. brasilense*, respectively.

The National Institute for Agricultural Research-INIAP has a collection of *Azospirillum* sp. and *P. fluorescens* strains isolated from the rhizosphere of corn plants, collected throughout the Ecuadorian Highlands. These strains have been characterized and evaluated, and as results the C2 strain of *Azospirillum* sp. and the *nI5* strain of *P. fluorescens* with a concentration of 1×10^9 ufc mL^{-1} have shown the best results in preliminary studies (Rivadeneira, 2012; Pincay, 2014; Sangoquiza et al., 2019). The objectives of this research are to evaluate the effect of these native Andean strains in the pro-

duction of fresh flour corn ("choclos" or "elotes") and estimate the benefit/cost of the inoculation.

2 Material and Methods

2.1 Study area

The experiment was established in a commercial corn production field located in the Province of Pichincha, Ecuador, in the parish of Amaguaña (0°23'9.87" S and 78°30'3.4" W), at an altitude of 2 675 masl, during the 2017-2018 cycle. The average temperature of Amaguaña is 17°C with an average rainfall of 960 mm (Bastidas, 2016).

2.2 Bacterial strains and bioinoculant

The inoculum was developed from the lyophilized strain *C*2 of *Azospirillum* sp., isolated from 'Laguacoto', parish Veintimilla, cantón Guaranda, province of Bolívar, and the strain *nl*5 of *P. fluorescens* isolated from 'Tunibamba' of the parish 'El Sagrario' cantón Cotacachi, province of Imbabura. The strains were collected from the rhizosphere of corn plants cultivated in the highlands of Ecuador (Carrera, 2012; Pincay, 2014). The strains are conserved at the laboratory of the Maize Program at the Experimental Station Santa Catalina of INIAP. The inoculum and the inoculation of the seeds were made as reported by Sangoquiza et al. (2019). Briefly, 1000 μL of 1% peptone were placed in the Eppendorf tubes, by shaking until the mixture was homogenized using a vortex. Subsequently, 50 μL of the inoculum were taken and placed in Petri dishes with the solid malic-acid Congo Red Agar culture medium for the case of *Azospirillum* sp., and *King B* for *P. fluorescens*. Subsequently, the inoculum was placed in an incubator at 30°C for 7 days. After this time, pure sections of the bacteria were taken and placed in Petri dishes with the specific growth media.

The bioinoculant was made in a liquid support with 2% molasses with sterile distilled water, pH 7, at a bacterial concentration of $1{\times}10^9$ ufc mL^{-1}. In 300 mL of the bioinoculant solution, 280 mL corresponded to the liquid support, and 20 mL to the bacteria (10 mL of *Azospirillum* sp. and 10 mL of *P. fluorescens*). The bacteria concentration was measured with a spectrophotometer (Thermo Scientific, GENESYS). The bacteria concentration was obtained by reaching the value of 1 in absorbance, which was confirmed by growth tests by dispersion on a plate. The ufc counting was performed using serial dilutions. The bioinoculant was applied directly to the seed at the time of sowing, as indicated by Yánez et al. (2010). Briefly, 420 seeds of maize were placed in a plastic bowl with a capacity of 5 L. Then, 200 mL of the bioinoculant was applied to the seed, mixing it uniformly to ensure contact with the seed surface. After inoculation, the seed was left to rest in the shade for an hour, before being used for sowing.

Bacteria viability test was performed with the remaining 100 mL of the bioinoculant. The viability evaluation was carried out by taking a sample of the bioinoculant in which serial dilutions were made, taking 0.1 mL of each dilution and sowing in Petri dishes with the specific culture medium for each bacterium. These were incubated at 30°C for 7 days. The presence of bacteria was determined by plate count.

2.3 Experimental design

The sowing was carried out in a sandy loam soil at the beginning of the rainy season in November, with the flour maize variety INIAP-101 (Caviedes, 2013). The treatments corresponded to: T1 (*Azospirillum* sp; 1×10^9 ufc mL^{-1}), T2 (P. fluorescens; 1×10^9 ufc mL^{-1}), T3 (Azospirillum sp. and P. fluorescens; 1×10^9 ufc mL^{-1}), T4 (control, conventional chemical fertilization) and T5 (absolute control). Chemical fertilization was applied only in the plots corresponding to the treatment T4. The fertilization, based on the results of the soil analysis (Table 1), was 57 kg of N ha^{-1}, 57 kg of P_2O_5 ha^{-1}, 10 kg K_2O ha^{-1}, 25 kg S ha^{-1}, and 10 kg of Mg ha^{-1}, distributing equally the nitrogen between sowing and hilling, which was carried out 45 days after sowing. The other nutrients were applied at sowing. The size of each plot was four furrows of 5.00 m long and 3.20 m wide, with 80 plants in each plot. The planting distance was 0.80 m between rows and 0.25 m between plants, with a density of 50 000 plants ha^{-1}. The nutritional content of the soil where the experiment was planted, analyzed in the Department of Soils of the Experimental Station Santa Catalina, is shown in Table 1.

Table 1. Nutritional values of the Amaguaña soil where the effect of inoculation of *Azospirillum* and *Pseudomonas* in flour maize was evaluated.

Nutrient	Value	Unit
N	57.0	ppm
P	11.0	ppm
S	4.70	ppm
K	0.59	meq 100 mL^{-1}
Ca	5.90	meq 100 mL^{-1}
Mg	1.90	meq 100 mL^{-1}
Zn	0.90	ppm
Cu	7.60	ppm
Fe	350	ppm
Mn	3.40	ppm
B	0.30	ppm
MO	4.40	%
pH	6.36	

The agronomic practices of the crop were carried out following the recommendations given to small farmers of the highlands of Ecuador (Yánez et al., 2013). In short, a plowing pass and a harrow pass were carried out to incorporate the remains of the previous crop (corn). During the development of the crop, the weeds were removed manually, and the insect pests were controlled with two applications of insecticides (Cypermethrin and Chlorpyrifos) at 60 and 120 days, with a dose of 1 L ha^{-1}. The crop was harvested and evaluated in a fresh state (fresh corn), at the growing stage R3 (milky stage), 150 days after planting (Yánez et al., 2013).

2.4 Variables evaluated

Agronomic evaluation was conducted at harvest, according to the International Maize and Wheat Improvement Center (CIMMYT) procedures for international trials (CIMMYT, 1999). The evaluation of the variables is detailed:

- **Plant height**: the length from the base of the plant to the point where the panicle begins to divide was measured on ten randomly selected plants in the central furrows of each plot. This variable was recorded in m using a height meter at harvest.
- **Root length**: at harvest, 10 plants were taken randomly form the central furrows of the plot. The aerial part of the plants was separated and the length of the root was measured from the base of the plant to the tip of the longest root with the help of a meter. This was measured in cm.
- **Ear length**: ten ears with bracts taken randomly from the central furrows of each plot were measured from the base to the tip of the ear with the help of a tape measure. This was measured in cm.
- **Ear diameter**: the central point of 10 randomly chosen ears from the central furrows with bracts of each treatment was measured with a caliper, the data were expressed in cm.
- **Yield**: ears with bracts, suitable for fresh consumption at R2-3 stage ("elote", "choclo"), from the two central furrows (40 plants) of each experimental plot were harvested. Fresh corn yield was recorded in kg, but data is shown as t ha^{-1}.
- **Inoculation effectiveness index (IEI)**: it was calculated as a percentage using the Equation 1 (Escobar et al., 2011).
- **Cost/benefit**: it was estimated based on the income from the sale of the fresh corn harvested and the production cost (inputs, labor, soil preparation, and indirect costs) of each treatment. The gross income (USD ha^{-1}) was estimated by multiplying the fresh corn yield (t ha^{-1}) by its commercial value (USD t^{-1}). The net profit per hectare was estimated by the difference between the gross income in dollars and the cost of production. The cost for each dollar obtained (CU) was calculated by dividing the cost of production (USD ha^{-1}) by the gross income (USD ha^{-1}), and the benefit cost ratio (B/C) was estimated by dividing the net profit (USD ha^{-1}) by the production cost (USD ha^{-1}).

$$IEI\,(\%) = \frac{(\text{yield of the inoculated treatment} - \text{yield of absolute control})}{(\text{yield of absolute control})} \times 100 \quad (1)$$

2.5 Statistical analysis

A completely randomized block design with six replications was used to evaluate the effect of three bioinoculants (T1, T2, and T3) and two controls (T5 and T6). The results were subjected to a normality Shapiro-Wilks modified test, and then, analysis of variance and Tukey's multiple comparison test ($p < 0{,}05$) were performed for all agronomic traits. The statistical program INFOSTAT was used for the analysis.

3 Results

Table 2 shows the results of the agronomical traits evaluated in the different treatments. Significant statistical differences ($p < 0{,}05$) were observed among the treatments for all traits. The absolute control, as expected, showed the lowest values, and lowest Tukey-test ranking, meaning the poorest agronomic performance. The use of conventional chemical fertilization (T4) showed the highest height of the plant with 2.44 m; although it did not differ statistically from the inoculated treatments (T1, T2 and T3), it did differ from the absolute control (T5), which obtained the shortest plants with 2.20 m.

The fresh corn yield obtained with the use of bioinoculants (T1, T2, and T3) did not differ statistically from the yield obtained using chemical fertilization (T4), according to Tukey test ($p < 0{,}05$). This was consistent with the observed performance of plant height, ear length, and root length. The IEI of the inoculation with *Azospirillum* sp. and *P. fluorescens* (T3) was 46.58%, almost twice than when it was done with the single bacteria (T1 or T2) (Table 2). The use of the bioinoculant with both isolates (T3, Azospirillum sp. and P. fluorescens) showed the best agronomical performance for ear diameter, yield, and IEI (Table 2). There were no significant differences ($p > 0{,}05$) between T3 and the chemical conventional fertilization control (T4) for any of the evaluated traits, except for ear diameter, where T3 obtained thicker ears than T4, with 21.47 cm and 20.13 cm, respectively.

The economic assessment showed the benefit/cost of the application of these bioinoculants on flour maize (Table 3). The inoculation of the seeds made with the combined biofertilizer T3 (*Azospirillum* sp. and *P. fluorescens*) got the highest net profit 3546.00 USD ha^{-1}, and the highest B/C ratio 1.35. Although the production cost of the combined bioinoculant (T3) was higher than the bioinoculants with a single isolate (T1 and T2), the gross income of T3 was higher due to the yield increase obtained when inoculating with both isolates (Table 2).

4 Discussion

4.1 Effect of the application of bioinoculants on agronomical traits of corn

The use of bioinoculants with *Azospirillum* sp. and *P. fluorescens* on fresh flour corn showed the same agronomic performance than using conventional chemical fertilization (Table 2). The results obtained in this study could be because these bacteria have the ability to fix nitrogen, solubilize phosphorus and produce plant growth promoting compounds (Aguirre and Espinosa Moreno, 2016; Rueda et al., 2016). These bacteria stimulated the growth and development of the flour corn plants that showed longer roots, taller plants, and thicker ears than the absolute control (T5). Cereals inoculated with these bacteria have shown a greater capacity to efficiently absorb water and nutrients from the soil (Sala et al., 2005; Oliveira et al., 2018; Pereira et al., 2020).

Bioinoculants based on *Azospirillum* and *Pseudomonas* strains have a high capacity to produce indole-acetic acid (IAA) causing root development and cell elongation. There are reports that assure the influence of *Azospirillum* on the formation of lateral roots due to nitrite secretion (Camelo et al., 2011; Bécquer et al., 2012). The production of IAA and the high sensitivity of the roots to this hormone are fundamental for the response to the inoculation of *Azospirillum* and *Pseudomonas*, where a greater radical development is frequently observed, which translates into a greater surface area for nutrient absorption, and thus, a greater development of the aerial part of the plant (García et al., 2007).

Table 2. Effect of the application of bioinoculants on agronomical traits in the cultivation of flour corn INIAP 101. Treatments: T1 (*Azospirillum* sp.), T2 (*P. fluorescens*), T3 (*Azospirillum* sp. and *P. fluorescens*), T4 (control, conventional chemical fertilization) and T5 (absolute control).

Treatment	Plant height (m)	Ear length (cm)	Ear diameter (cm)	Root length (cm)	Fresh corn yield (t ha^{-1})	IEI (%)
T1	2.37 ab*	38.33 a	21.20 a	38.67 a	16.72 b	22.68 b
T2	2.42ab	35.83 ab	21.00 a	32.67 bc	17.05 b	23.68 b
T3	2.33 ab	37.50 ab	21.47 a	37.00 ab	19.70 a	46.58 a
T4	2.44 a	36.33 ab	20.13 b	34.17 abc	17.12 ab	-
T5	2.20 b	32.33 b	18.47 c	31.00 c	13.58 c	0.00 c

IEI = Inoculation effectiveness index. *Different lowercase letters mean significant statistical difference according to Tukey test ($p < 0{,}05$).

The flour corn maize INIAP 101 showed an increase in the plant height, ear length and diameter of the inoculated plants, compared with the absolute control (Table 2). These results agree with Piscoya and Ugaz (2016), who pointed out that the Azospirillum genera showed an increase in the height, number of leaves and diameter of stems in the cultivation of hard corn; meanwhile Piromyou et al. (2011) demonstrate the beneficial action of individual and mixed inoculation of beneficial microorganisms in the cultivation of dent corn by improving their radical functioning in the absorption of the nitrogen by externally invading the corn root, favoring the synthesis of plant growth promoting substances.

The C2 strain of *Azospirillum* sp. and the nl5 strain of *P. fluorescens* used in this study have shown their capacity to promote nitrogen and phosphorous absorption before. Sangoquiza et al. (2019) reported a higher accumulation percentage of nitrogen and phosphorous in leave tissue of INIAP-101 plants inoculated with these isolates. Similar studies of the effect of *Azospirillum* sp. showed a higher percentage of nitrogen in corn leaf tissue (Ortiz, 2010), while the inoculation of *A. brasilense* and *P. fluorescens* increased the total phosphorus content by 187 kg ha^{-1} (Faggioli et al., 2003).

4.2 Inoculation effectiveness index (IEI) of the bioinoculants

For IEI, the treatment T3 showed statistically significant differences with treatments T1 and T2, according to Tukey-test ($p < 0{,}05$) (Table 2). These results indicated that the combination of Azospirillum and P. fluorescens favored corn performance, which suggests an associative symbiosis that can improve root morphology and physiology, achieving better use of water and nutrients such as nitrogen and phosphorus, generating better quality and development of the grain (Gálvez et al., 2014). Martins et al. (2018) pointed out that the effects of these microorganisms on plant development have favored the performance of various crops, when applied alone or in combination, achieving greater colonization and increasing the production. A more detailed review of the benefits of biofertilizers was recently published by Zambrano-Mendoza et al. (2021).

4.3 Economic assessment of the use of the bioinoculants

The analysis of the economic parameters showed how advantageous the application of these bioinoculants were by promoting a good development of the inoculated plants and greater economic performance (Table 3). The highest cost of production was obtained with T4 (conventional chemical fertilization control), while the lowest cost of production was obtained with T5 (absolute control), where no fertilization nor bioinoculant was applied. The main difference among the production costs of each treatment was given by the value of the chemical fertilizer and the cost of its application. In relation to the conventional chemical recommendation (T4), the use of the bioinoculant T3 (*Azospirillum* and *P. fluorescens*) allowed a saving of USD 281.12 ha^{-1}, which represents a decrease of approximately 16% in the production cost, without significantly affecting yield (Table 2). This shows that it is possible to substitute the use of chemical fertilizers by bioinoculants without affecting the production of corn, opening the opportunity to more sustainable and environmentally friendly production systems.

Table 3. Economic assessment of the application of bioinoculants in the flour corn INIAP 101 in the highlands of Ecuador.

	Treatment	Production cost (USD ha^{-1})	Raw Income (USD ha^{-1})	Net profit (USD ha^{-1})	CU* (USD)	Benefit/Cost (USD)
T1	*Azospirillum* sp.	1505.74	3009.60	1503.86	0.50	1.00
T2	*P. fluorescens*	1505.74	3069.00	1563.26	0.49	1.04
T3	*Azospirillum* sp. + *P. fluorescens*	1511.74	3546.00	2034.26	0.43	1.35
T4	Control, chemical fertilization química	1792.86	3081.60	1288.74	0.58	0.72
T5	Absolute control	1491.86	2444.40	952.54	0.61	0.64

*CU = Cost for each dollar obtained.

Many corn farmers in the highlands do not use chemical fertilizers at all, resembling treatment T5 (absolute control). Using *Azospirillum* and *P. fluorescens*, farmers may have the possibility to duplicate their net profit from 952.54 USD ha^{-1} to 2034.26 USD ha^{-1} with an additional investment of approximately 20.0 USD ha^{-1} (Table 3). Further studies in several environmental conditions could clarify this possibility.

The B/C of the fresh corn production using the bioinoculant T3 (*Azospirillum* and *P. fluorescens*) increased by 87.5% in relation to the conventional chemical fertilization (T4) (Table 3). This value is higher than the increase of 56.0% reported by García et al. (2012), and the increase of 36.0% reported by García et al. (2007), when evaluated the effect of the application of A. brasilense on dent corn in northern Mexico. In economic terms, these results showed that the inoculation with plant growth promoting bacteria (*Azospirillum* sp. and *P. fluorescens*) increased the net profit and the B/C ratio of the cultivation of corn; therefore, the use of these bioinoculants could generate an economically viable technology for the production of flour corn in the Andean Region.

5 Conclusions

The inoculation with *Azospirillum* sp. improved the yield of fresh corn ("choclo"), increased the development of the root, and the diameter and the length of the cob compared to the control. The inoculation with *P. fluorescens* showed higher yield and ear diameter than the control. The combination between *Azospirillum* sp. and *P. fluorescens* significantly increased fresh corn yield by 46.58% in relation to the control without fertilization. The yield of the plants treated with chemical fertilizer was similar to the yield obtained with the plants inoculated with these microorganisms. The combination of Azospirillum sp. and P. fluorescens produced the highest net gain and B/C ratio, increasing by 87.5% the B/C of conventional chemical fertilization.

Azospirillum sp. and *P. fluorescens* reduced the use of synthetic fertilizers by approximately 50%, lowering the cost of production. Hence, it is feasible to substitute the use of synthetic fertilizers for biofertilizers, opening the opportunity for a sustainable and environmentally friendly maize production system in the Ecuadorian highlands.

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Author Contributions

CASC; Research, Writing. JLZM; Writing, review and editing. MBG; Conceptualization. KJC; Validation.

References

Aguirre, J. and Espinosa Moreno, J. (2016). Crecimiento y rendimiento de capsicum annuum l. inoculado con endomicorriza y rizobacterias. *Revista mexicana de ciencias agrícolas*, 7(7):1539–1550. Online:https://n9.cl/hmfv8.

Bastidas, W. (2016). Guía climática agroecoturística para el cantón quito-provincia de pichincha 2014. Master's thesis, Universidad Central del Ecuador.

Bécquer, C., Lazarovits, G., Nielsen, ., Quintan, M., Adesina, M., Quigley, L., Lalin, I., and Ibbotson, C. (2012). Efecto de la inoculación con bacterias rizosféricas en dos variedades de trigo. fase ii: invernadero. *Revista mexicana de ciencias agrícolas*, 3(5):985–997. Online:https://bit.ly/3ekmwhF0.

Boada, R. and Espinosa, J. (2016). Factores que limitan el potencial de rendimiento del maíz de polinización abierta en campos de pequeños productores de la sierra de ecuador. *Siembra*, 3(1):67–82. Online:https://bit.ly/2TDxHKo.

Camelo, M., Vera, S., and Bonilla, R. (2011). Mecanismos de acción de las rizobacterias promotoras del crecimiento vegetal. *Ciencia & Tecnología Agropecuaria*, 12(2):159–166. Online:https://bit.ly/2ZEW51X.

Carrera, A. (2012). Caracterización bioquímica, molecular y funcional del banco de cepas de azospirillum spp. del iniap aisladas de la rizósfera del cultivo de maíz (zea mays l.) de la sierra ecuatoriana. Master's thesis, Escuela Superior Politécnica del Ejercito.

Caviedes, C. (2013). *Variedad de maíz blanco precoz. Quito, EC, INIAP, Estación Experimental Santa Catalina, Programa de Maíz*. INIAP.

CIMMYT (1999). *Manejo de los ensayos e informes de los datos para el Programa de Ensayos Internacionales de Maíz del CIMMYT*. CIMMYT.

Díaz-Blanco, P. and Márquez-Reina, E. (2011). Validación de los biofertilizantes azotobacter, rhizobium y fosforina en cuatro sistemas de cultivos en condiciones de producción. *Avances*, 13(2):1–9. Online:https://bit.ly/36vobhK.

Escobar, C., Horna, Y., Carreño, C., and Mendoza, G. (2011). Caracterización de cepas nativas de azotobacter spp. y su efecto en el desarrollo de lycopersicon esculentum mill."tomate" en lambayeque. *Scientia Agropecuaria*, 2(1):39–49. Online:https://bit.ly/3V12cHR.

ESPAC (2018). Visualizador de estadísticas agropecuarias del ecuador espac. INEC. Online:https://bit.ly/2XyBaLp0.

Faggioli, V., Cazorla, C., Vigna, A., and Berti, M. (2003). Fertilizantes biológicos en maíz: ensayo de inoculación con cepas de azospirillum brasilense y pseudomonas fluorescens. Technical report, Instituto Nacional de Tecnología Agropecuaria. Online: https://bit.ly/36zMtqE.

Gálvez, G., Magallón, R., and Torres, L. (2014). Evaluación de biofertilizantes líquidos en la producción de elote y grano en maíz. *e-Cucba*, 1(1):15–20. Online:https://bit.ly/36v53Av.

García, J., Mendoza-Herrera, A., and Mayek-Pérez, N. (2012). Efecto de azospirillum brasilense en el rendimiento del maíz en el norte de tamaulipas, méxico. *Universidad y ciencia*, 28(1):79–84. Online:https://bit.ly/3gtDLPl.

García, J., Moreno-Medina, V., Rodríguez-Luna, I., Mendoza-Herrera, A., and Mayek-Pérez, N. (2007). Efecto de cepas de azospirillum brasilense en el crecimiento y rendimiento de grano del maíz. *Revista Fitotecnia Mexicana*, 30(3):305–305. Online:https://bit.ly/2X5L48i.

Glick, B. (2012). Plant growth-promoting bacteria: mechanisms and applications. *Scientifica*, 2012. Online:https://bit.ly/3GyR2Wi.

Grageda, O., Díaz-Franco, A., Peña-Cabriales, J., and Vera-Núñez, J. (2012). Impacto de los biofertilizantes en la agricultura. *Revista Mexicana de Ciencias Agrícolas*, 3(6):1261–1274. Online:https://bit.ly/2ZEOAIt.

Guzmán, A. (2012). Aislamiento y caracterización de bacterias solubilizadoras de fósforo a partir de cuatro suelos de la provincia de chimborazo. Master's thesis, Escuela Superior Politécnica de Chimborazo.

Martínez-Reyes, L., Aguilar, C., Carcaño, M., Galdámez, J., Gutiérrez, A., Morales, J., Martínez, F., Llaven, J., and Gómez, E. (2018). Biofertilización y fertilización química en maíz (zea mays l.) en villaflores, chiapas, méxico. *Siembra*, 5(1):26–37. Online:https://bit.ly/2ABEUUQ.

Martins, T., Freitas Júnior, S., Luz, L., Marco, C., and Vásquez, E. (2018). Inoculation efficiency of azospirillum brasilense on economising nitrogen fertiliser in landrace popcorn. *Revista Ciência Agronômica*, 49:283–290. Online:https://bit.ly/3gsAtvZ.

Oliveira, I., Fontes, J., Pereira, B., and Muniz, A. (2018). Inoculation with azospirillum brasiliense increases maize yield. *Chemical and Biological Technologies in Agriculture*, 5(1):1–9. Online:https://bit.ly/3CqtMWe.

Ortiz, G. M. (2010). Evaluación del efecto de cuatro métodos de inoculación de dos cepas de azospirillum spp., en el cultivo de maíz (zea mays l.), variedades iniap 122 y 102, en las provincias de imbabura y pichincha. Master's thesis, Universidad Técnica de Ambato.

Pereira, N., Galindo, F., Gazola, R., Dupas, E., Rosa, P., Mortinho, E., and Filho, M. (2020). Corn yield and phosphorus use efficiency response to phosphorus rates associated with plant growth promoting bacteria. *Frontiers in Environmental Science*, 8:40. Online:https://bit.ly/2A7Th2X.

Pincay, A. (2014). Caracterización y evaluación de bacterias pseudomonas sp. solubilizadoras de fósforo, presentes en la rizósfera de maíz (zea mays l). Master's thesis, Universidad de las Fuerzas Armadas.

Piromyou, P., Buranabanyat, B., Tantasawat, P., Tittabutr, P., Boonkerd, N., and Teaumroong, N. (2011). Effect of plant growth promoting rhizobacteria (pgpr) inoculation on microbial community structure in rhizosphere of forage corn cultivated in thailand. *European Journal of Soil Biology*, 47(1):44–54. Online:https://bit.ly/2AWUKcz.

Piscoya, E. and Ugaz, Z. (2016). Efecto de azospirillum, azotobacter y enterobacter spp. nativas con 50% de fertilizante químico en el desarrollo vegetativo y rendimiento de zea mays l."maíz.ªmarillo duro en lambayeque. Master's thesis, Universidad Nacional Pedro Ruiz Gallo.

Rivadeneira, M. (2012). Evaluación del biofertilizante a base de cepas de azospirillum spp. en el cultivo de maíz (zea mays l.) "iniap-111 guagal mejorado", en complemento con tres tipos de fertilización y dos métodos de inoculación, en la granja laguacoto ii, provincia bolívar. Master's thesis, Universidad Estatal de Bolívar.

Rueda, D., Valencia, G., Soria, N., Rueda, B., Manjunatha, B., Kundapur, R., and Selvanayagam, M. (2016). Effect of azospirillum spp. and azotobacter spp. on the growth and yield of strawberry (fragaria vesca) in hydroponic system under different nitrogen levels. *Journal of Applied Pharmaceutical Science*, 6(1):048–054. Online:https://bit.ly/3el2CTK.

Ruiz, J. (2015). Evaluación de cepas de (azospirillum sp.) y mallas sombra de colores sobre la morfología y bioquímica de la lechuga. Master's thesis, Universidad Autónoma Agraria Antonio Narro.

Sala, V., Freitas, S., Donzeli, V., Freitas, J., Gallo, P., and Silveira, A. (2005). Ocorrência e efeito de bactérias diazotróficas em genótipos de trigo. *Revista Brasileira de Ciência do Solo*, 29:345–352. Online:https://bit.ly/2AdumuA.

Sangoquiza, C., Yánez, C., and Borges, M. (2019). Respuesta de la absorción de nitrógeno y fósforo de una variedad de maíz al inocular azospirillum sp. y pseudomonas fluorescens. *ACI Avances En Ciencias E Ingenierías*, 11(1):8–19. Online:https://bit.ly/2M3aX2o.

Santoyo, G., Moreno-Hagelsieb, G., del Carmen, M., and Glick, B. (2016). Plant growth-promoting bacterial endophytes. *Microbiological research*, 183:92–99. Online:https://bit.ly/3c2xBCp.

Urrutia, E. (2019). Aplicación de bioestimulantes trihormonales en el cultivo de maíz (zea mays l.) variedad chingasino para rendimiento de choclo. Master's thesis, Universidad Nacional del Centro del Perú.

Yánez, G., Clavijo, F., and Cool Zambrano, C. (2010). Biofertilizante. fertibacter-maíz. Technical report, INIAP.

Yánez, G., Zambrano, J., Caicedo, M., and Heredia, J. (2013). Guía de producción de maíz de altura. Technical report, INIAP.

Zambrano-Mendoza, J., Sangoquiza-Caiza, C., Campaña-Cruz, D., and Yánez-Guzmán, C. (2021). *Use of Biofertilizers in Agricultural Production*. IntechOpen.

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Scientific paper/ Artículo científico

Agricultural Sciences

Effect of plant density on yield components of common bean grown under inter-Andean mountain conditions of Ecuador

Efecto de la densidad de plantas sobre los componentes del rendimiento de fréjol cultivado en condiciones de campo en un valle interandino de Ecuador

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Abstract

Common bean is an important crop due to its high nutritional value. However, its production in Ecuador has decreased due to biotic and abiotic factors. Understanding the mechanisms that determine the yield components of this crop is essential to establish strategies that allow increasing the yield. In this study, the plant density was modified to evaluate its impact on yield and its two main components, the grain number and grain weight under field conditions in an Andean region of Ecuador. Two experiments planted on different dates were performed, where two planting densities 4 and 11 plants m^{-2} were evaluated. The effect of the treatments was studied on the length of the period, from emergence to anthesis, the number of full and empty pods, grain number, 100 grain weight and grain yield. The results indicate that the plant density has a significant effect ($p<0.05$) on the yield, reaching an average of 257.15 g m^{-2} in high density, and 151.45 g m^{-2} in low density. The yield main components showed a different response to plant density modification; the grain number exhibited a strong variability and was positively associated with final grain yield ($p<0.05$) while the grain weight was not affected.

Keywords: Grain number, grain weight, *Phaseolus vulgaris*, plant density, plant population, yield components.

Resumen

El fréjol es un cultivo importante debido a su alto valor nutritivo. En los últimos años la producción en Ecuador de este cultivo ha disminuido drásticamente debido entre otros factores a ineficientes procesos y falta de tecnificación en la producción. Entender cómo se generan y determinan los componentes del rendimiento del grano es primordial para diseñar estrategias que permitan aumentar el rendimiento del cultivo. En este estudio, se modificó la densidad de plantas con el objetivo de evaluar su impacto sobre el número de granos, peso de granos y rendimiento, bajo condiciones de campo en una región andina de Ecuador. Se realizaron dos experimentos sembrados en fechas distintas, donde se evaluaron densidades de plantas contrastantes 4 y 11 plantas m^{-2}. El efecto de los tratamientos se estudió sobre la duración del periodo emergencia - antesis, el número de vainas llenas y vanas, el número de granos, el peso seco de 100 granos y el rendimiento de grano. Los resultados indican que la densidad de plantas tiene un efecto significativo ($p<0,05$) sobre el rendimiento, alcanzando un promedio de 257,15 g m^{-2} en alta densidad y 151,45 g m^{-2} en baja densidad. Los componentes principales del rendimiento mostraron una respuesta distinta a la modificación de la densidad de plantas; el número de granos presentó una fuerte variabilidad y fue positivamente asociado con el rendimiento final del grano ($p<0,05$), mientras que el peso del grano no fue afectado.

Palabras clave: Componentes del rendimiento, densidad de siembra, fréjol, número de granos, peso de grano, *Phaseolus vulgaris*, población de plantas.

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1 Introduction

Bean (*Phaseolus vulgaris* L.) is an important crop due to its high nutritional value, containing between 20 - 30% protein (Celmeli et al., 2018), and is one of the important crops sowed in several Andean areas of Ecuador (Valarezo et al., 2008; Bustamante, 2017). Like other legumes, this species is used in crop rotation to reduce disease-causing agents, and to maintain soil fertility through atmospheric nitrogen fixation (Vásquez et al., 2015). In recent years the cultivated area and production of bean in Ecuador has decreased drastically, from 2011 to 2019 an approximate decrease of 50% was estimated (FAOSTAT, 2019). Among the factors that have contributed to the reduction in harvested area are droughts, incidence of pathogens, poor crop management, low technification and increased production costs, favoring the importation of bean grain (Sistema de Información Publica Agropecuaria de Ecuador, 2018).

Increasing the profitability of this crop requires improving productive efficiency and reducing production costs, thus plant density management would play an important role (Calero-Hurtado et al., 2018). Crop yield would respond to the modification of plant density, because the number of plants per unit area would be related to the growth rate of the crop under solar radiation and temperature (Boada and Espinosa, 2016).

Traditionally, farmers use plant densities between 15 600 to 20 800 plants ha^{-1} with furrow spacings of 0.80 to 1.00 m for manual weeding (Parreira et al., 2011), paying little attention to yield response and its components. Bean genotypes can vary when generating reproductive structures due to phenotypic plasticity in response to plant density (Andrade and Abbate, 2005), with consequences in plant cover, biomass, competition with weeds, generation of yield components and therefore in final grain yield.

Some studies show that increased density can avoid water loss. As the distance between rows is reduced and the distance between plants is maintained it is possible to increase the vegetative cover of the crop, and consequently reduce direct water losses by evaporation by covering the soil more quickly (Osuna et al., 2012). In addition, for the bean crop to have competitive advantages with weeds, increasing the density allows total soil cover once the crop reaches full vegetative development (Parreira et al., 2011).

Number of grains (NG) and average grain weight (WG) are major components of grain crop yield (Peltonen-Sainio et al., 2007; Sadras, 2007; Slafer et al., 2014). In many crops, NG is related with yield, while grain weight shows less variation; however, it has also been found that WG can compensate for the decrease in NG when the source decreases (Ghobadi et al., 2006; Labra et al., 2017).

Studies in bean have evaluated the effect of plant density on yield mainly under tropical and Mediterranean agroclimatic conditions, however, the response of yield components may vary in different genotypes and environments. For example, Soratto et al. (2017) evaluated densities of 5, 7 and 9 plants m^{-2}, and only found yield differences in one genotype with the highest plant density. In another study, Ahmed et al. (2016), evaluated densities of 4, 5, 7 and 14 plants m^{-2}, and report that grain weight increased with the lowest density (4 plants m^{-2}), while yield was maximized with 5 plants m^{-2}. On the other hand, Gabisa et al. (2017), studied high plant densities: 12, 15, 19 and 25 plants m^{-2}, indicating that densities of 14 and 19 plants m^{-2} exhibited the highest yields; this background suggests that the response to plant density is conditioned by environment and genotype. To date, there is little information on the individual response of numerical yield components and their relationship with grain yield when resource supply is modified in local bean genotypes under mountainous environments in the Andean zones of Ecuador.

A better understanding of yield determination and its components is a prerequisite for developing strategies aimed at increasing yield through plant breeding, as well as for agronomic crop management (Foulkes et al., 2011). The objective of the research is to determine the effect of plant density modification on yield components of beans grown in an Andean region of Ecuador.

2 Materials and Methods

2.1 Location of the experiment and crop management

The study was carried out at La Argelia Experimental Station of the National University of Loja (4°02′19.2″S 79°12′00.6″W) at 2150 m.a.s.l., in a silty loamy soil. Percal bush bean cv. Percal, widely cultivated in the province of Loja, Ecuador, was used as planting material. Prior to sowing, a seed germination test was carried out, showing a germination higher than 95%. Weeds were controlled manually approximately every 20 days, starting from the first trifoliate leaf stage until the grain filling stage, covering the critical period of weed interference reported by Ngouajio et al. (1997). When the first symptoms of damage caused by phytopathogens were observed, preventive applications were made using synthetic fungicide and insecticide. In addition, when rainfall was scarce, supplemental irrigation was applied by sprinkling. Before planting, bocashi was incorporated 7 t h^{-1}, and later, fertilization was applied with 120 kg ha^{-1} N partialized at phenological stages V4 and R6 (Fernández de Córdova et al., 1986).

2.2 Experimental Design

The trial was arranged in a factorial design with a randomized distribution. Two experiments were set up with different sowing dates, Experiment 1 (E1) sown on October 26, 2018 and Experiment 2 (E2) sown on November 26, 2018. The experiments were established at two sowing densities, 11 plants m^{-2} (0.60 m between furrows and 0.30 m between plants) and 4 plants m^{-2} (0.80 m between furrows and 0.60 m between plants), placing two seeds per site. The plots were 3.20 m long and 2.80 m wide, with three replications for each treatment.

2.3 Measurements and statistical analysis

Crop phenology was recorded weekly according to the scale proposed by Fernández de Córdova et al. (1986), from sowing to harvest maturity. Meteorological data on temperature, relative humidity and precipitation were recorded daily at La Argelia-Loja meteorological station (INAMHI) located near the experiment.

At harvest maturity, all plants were taken from 1 m linear of the two central rows of each plot, avoiding the plants at the edges, and the number of grains, the number of full and empty pods were counted. The dry weight of the grains was determined after leaving them in the oven for 3 days at 65 $\pm$ 5 °C. The number and weight of grains were used to calculate the grain yield.

A factorial analysis of variance and a Fisher's test of means ($\alpha = 0.05$) were used to evaluate the effect of the treatments. Prior to the ANOVA, the statistical assumptions of normality, independence of observations and homogeneity of variance were evaluated. The model described by Equation 1 was used to evaluate the differences between treatments.

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \quad (1)$$

Where y_{ijk} represents the observations corresponding to the i-th level of the factor density and j to the level of the factor experiment; μ represents the overall mean; α_i is the effect produced by the i-th level of the factor plant density; β_j is the effect produced by the j-th level of the factor experiment; $(\alpha\beta)_{ij}$ is the effect produced by the interaction between density and experiment; and ε_{ijk} represents the experimental error.

3 Results and Discussion

3.1 Phenology and climate

The duration of the sowing-anthesis stage was not affected by sowing density or sowing date ($p>0.05$); on average the crop in the two experiments took 61.72 ($\pm$ 0.74) days to reach flowering (Table 1). The crop cycle from sowing to harvest lasted approximately 119 and 125 days for the high and low density treatments, respectively. The small difference in the duration of the stages and the crop cycle between experiments and densities could be related to the small temperature variation experienced by the plants of the different treatments (Figure 1), since this is the main factor that modifies crop ontogeny (Luo, 2011). A previous study with the same cultivar indicates that the crop took 141.67 days to harvest maturity; however, the average temperature of the cycle was 12.47 °C (Goyes, 2014), suggesting that this difference would occur by the colder tem-

peratures that delayed the thermal accumulation of the crop.

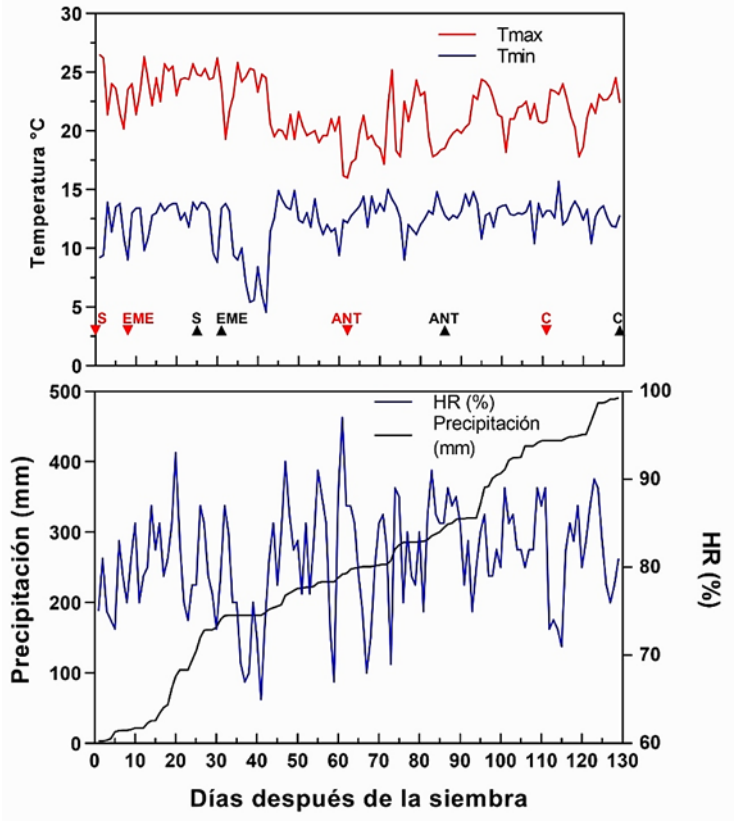

Figure 1. Diagram of the duration of phenological stages and climatic variables of precipitation, temperature and relative humidity during the growing cycle of the two experiments. Red triangles indicate experiment 1 and black triangles indicate experiment 2. S (sowing), EME (emergence), ANT (anthesis), C (harvest).

3.2 Number of pods

Plants planted at low density (4 plants m^{-2}) had a higher number of pods $plant^{-1}$ compared to those planted at higher density (11 plants m^{-2}), increasing the number of pods by 36.2 and 29.2% in experiment 1 and 2, respectively ($P<0.05$). Also, significant differences were found between the experiments (Table 1), observing that the averages of experiment 2 were lower ($P<0.05$), maybe because experiment 2 had an incidence of pathogenic fungi that could affect the final number of pods (the incidence of diseases was not evaluated). When the number of empty pods was analyzed, no statistical differences were found, suggesting that there were sufficient resources for the establishment and growth of grains per pod at the densities evaluated.

The increment in the number of pods in plants grown at low density suggests that it is a consequence of lower intraspecific competition, which would result in greater availability of resources that could have generated increases in the number of branches and pods. Some grain crops, including bean, have the ability to modify their structure in response to source modification; previous work indicates that pod number is one of the most sensitive components to density modification in bean (Bennett et al., 1977; Mondo and Nascente, 2018). The results of this research agree with previous results (Abubaker, 2008; Osuna et al., 2012; Gabisa et al., 2017), in which when increasing the number of plants decreases the number of pods established per plant in bean crop.

Table 1. Average yield and its components, and duration of the sowing-anthesis stage.

E	DS	Days to anthesis	Pods Plant^{-1}	Empty Pods Plant^{-1}	Pods m^{-2}	Grains Pods^{-1}	Grains Plant^{-1}	Grains m^{-2}	Weight of 100 grains (g)	Performance (g m^{-2})
1	11	61.67	13.5	4.5	49.5	4.98	56.17	624.57	40.41	254.28
1	4	62	21.17	4.83	19.33	4.87	96.83	402.83	45.52	183.93
2	11	60.73	10.68	4.9	53.9	5.06	52.69	585.96	43.73	260.02
2	4	62.47	15	6.83	31.33	5.28	70.83	294.67	38.71	118.97
E. st		0.62	1.4	0.53	2.35	0.1	6.76	52.04	1.62	25.43
E		ns	*	ns	ns	ns	ns	ns	ns	ns
DS		ns	*	ns	*	ns	*	*	ns	*
ExDS		ns	ns	ns	ns	ns	ns	ns	ns	ns

*Significant effect p<0.05; E.st: standard error; ns: not significant; E: experiment; SD: plant density (plants m^{-2}). Values are averages of three replicates.

3.3 Number of grains

No statistical differences were found in the density treatments and experiments evaluated in the NG pod^{-1}, on average 5 ($\pm$ 0.17) grains were obtained in each pod. The number of grains remaining established in each pod would be related to the amount of available soil resources and photosynthesis (Hadi et al., 2006; Lake et al., 2019). The results obtained indicate that there was no limitation for grain formation in pods in the density ranges explored (Table 1), suggesting that when source availability is modified by plant density, the establishment of pod number plant^{-1} is more sensitive to the environment than NG pod^{-1}.

Both NG plant^{-1} and NG m^{-2} were affected by plant density (P<0.05). As previously shown, plants grown at low density had a higher number of pods, with no differences in the number of established grains per pod; consequently, NG plant^{-1} increased by 42 and 26 % in E1 and E2, respectively, compared to plants sown at high density (Table 1), observing a positive relationship between the number of pods plant^{-1} and NG plant^{-1} (Figure 2A).

On the contrary, when NG m^{-2} is used, it is observed that this component is significantly higher in the high-density treatment, because there was a greater number of plants per unit area in this treatment, thus increasing the number of reproductive structures. Although the plants grown in low density established a greater number of pods plant-1, this was not enough to compensate the NG m^{-2} nor the grain yield, observing a negative relationship between the number of pods plant^{-1} and yield (Figure 2B). Previous work also shows a decrease in NG plant^{-1}, when the plant population is increased and the spatial arrangement of the bean crop is modified (Osuna et al., 2012; Escalante-Estrada et al., 2015). One way to improve bean yield may be to improve the number of pods per plant, which as shown in this study responds satisfactorily to resource modification and is associated with final grain yield.

3.4 Grain weight

Grain weight was not affected by density treatment in the two experiments (Table 1). On average, the dry weight of 100 grains at harvest was 42.09 g ($\pm$ 3.1) in all treatments, confirming that this component is more stable than NG, supporting the idea that WG is a conservative trait and not very sensitive to the modification of the source-destination relationship as has been seen in other grain crops such as soybean and corn (Sadras, 2007). Studies with determined and undetermined habit genotypes in different environments also show that WG has little variation when plant density is modified (Osuna et al., 2012; Escalante-Estrada et al., 2015; Soratto et al., 2017). These results indicate a high challenge to increase grain weight possibly due to the strong interaction of genotype and environment exerted on this component in bean as reported by Pereira et al. (2017).

3.5 Yield

Grain yield was significantly affected by plant density in both experiments ($P<0.05$). A positive response of yield to the increase in the number of plants m^{-2} was observed, because in a first stage the number of plants per unit area would condition the formation of reproductive structures in the absence of restriction of nutrient resources and solar radiation (Slafer and Rawson, 1994; Kruk and Satorre, 2003; Véliz et al., 2021a).

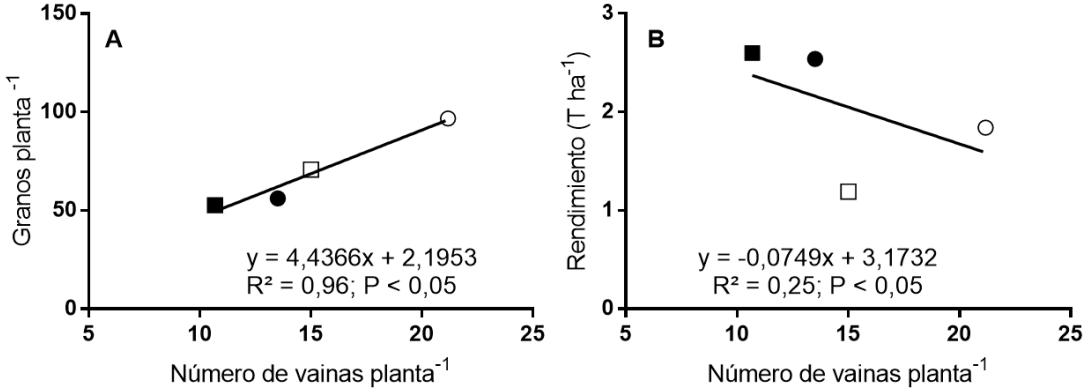

Figure 2. Relationship between the number of pods per plant and the number of grains per plant (A), and between the number of pods per plant and crop yield (B). Circles represent experiment 1 and squares represent experiment 2, filled symbols indicate density 11 plants^{-2} and empty symbols indicate density 4 plants m^{-2}. Each point is the average of three replicates.

The results suggest that although soil resources may have decreased at high density due to intraspecific competition, this was not limiting for yield gain in the high-density treatment, probably due to higher biomass generation per unit area, which translated into higher interception of photosynthetically active radiation (De Bruin and Pedersen, 2009; Véliz et al., 2021b), favoring the establishment of larger harvested organs as in previous studies (Egli, 1988; Soratto et al., 2017; Calero-Hurtado et al., 2018).

The yield in this research greatly exceeded previous studies (Calero-Hurtado et al., 2018) where higher densities were used such as 16 plants m^{-2} with grain yield of 1 t ha^{-1}, even surpassing investigations where densities between 22 to 28 plants m^{-2} were evaluated (Puente, 2009), possibly due to a low efficiency in those production systems, which could imply higher production costs due to the higher number of plants per unit area.

Relationships between yield and its components were explored in this research, the results of which indicate that the number of grains and pods per unit area are closely related with yield, as has been seen in other grain crops (Peltonen-Sainio et al., 2007; Sadras, 2007; Slafer et al., 2014). On the other hand, WG is not related with yield (Figure 3 A, B, C). As previously shown NG and WG possess different sensitivity to density modification in bean, indicating that WG in bean is a stable trait in contrast to NG

Our results are similar to studies conducted in temperate cereals (Reynolds et al., 2021), where yield tends to be better related to grain number while WG is insensitive or marginally responsive when resource input is modified during grain filling (Serrago et al., 2013; Aisawi et al., 2015; Bonelli et al., 2020).

These results indicate that beans, as well as other grain crops such as cereals, are also limited by the destination or sink, because the modification of source resources, as a consequence of the change in the number of plants per unit area, modified the yield mainly by changes in the NG and not in the WG. These results support the idea that the little variation observed in WG may reflect an adaptive evolutionary response, and that reducing intraspecific variability in seed size and weight would

allow optimal seed size, balancing the survival of individuals and the number of progeny produced as indicated by Sadras and Denison (2009) and Sadras and Slafer (2012).

Incrementing bean yield would imply increasing its two components to avoid possible trade-offs between NG and WG, however, traditionally grain crop improvement has focused on increasing NG (Mason et al., 2008; Sadras and Lawson, 2011). While WG has had less attention (Castillo et al., 2017), the low variability of PG found in this study highlights the need to improve this component, which could help increase yield in bean crop.

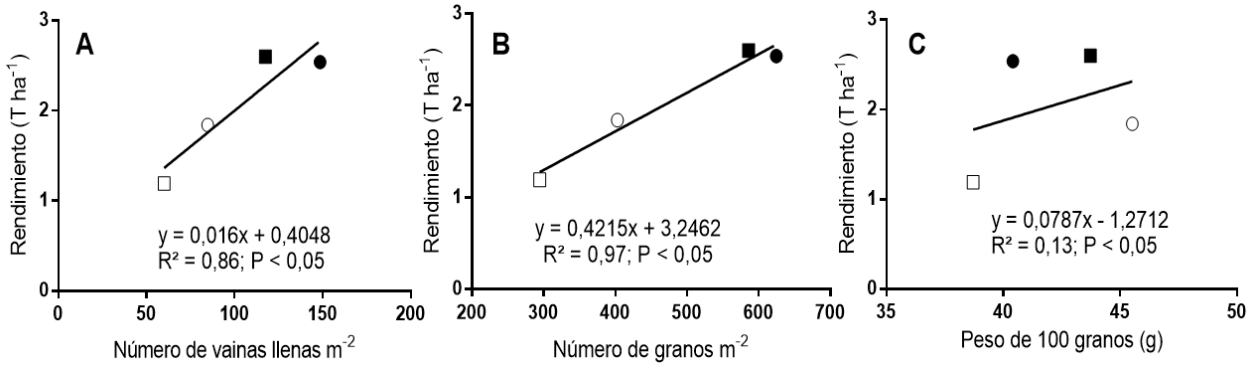

Figure 3. Relationship between yield and number of pods m^{-2} (A), number of grains m^{-2} (B), and 100-grain weight (C). Circles represent experiment 1 and squares represent experiment 2, filled symbols indicate density 11 plants^{-2} and empty symbols indicate density 4 plants m^{-2}. Each point is the average of three replicates.

4 Conclusions

Increasing bean plant density from 4 to 11 plants m^{-2} led to grain yield increases averaging $\approx 70\,\%$ in the two experiments. A different response of yield components to plant density modification was evidenced, NG is highly sensitive and increased by $\approx$ 73 % due to increase in the number of pods per unit area at high density. Furthermore, NG is closely related with final grain yield ($R2 = 0.97$), while grain weight was not affected by plant density modification, reaching on average 42 ± 3 g in all treatments.

To date, there is little evidence that has quantified the response of the numerical components of bean yield and their association with final yield under an ecophysiological approach in Andean environments, where soil and climatic conditions differ significantly from previous studies. Therefore, these results constitute a basis for designing strategies oriented to increase the yield of this important crop under these agroclimatic conditions, especially to improve grain weight and size, which has little response to resource supply.

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Author Contributions

SCV; Conceptualization, Formal analysis, Supervision, Writing-original draft, Writing-review and editing. EIVS; Research, Data Curation, Writing – original draft. AGG; Investigation. HMM; Research, Writing-review and editing. CAMU; Writing-review and editing.

References

Abubaker, S. (2008). Effect of plant density on flowering date, yield and quality attribute of bush

beans (phaseolus vulgaris l.) under center pivot irrigation system. *American Journal of Agricultural and Biological Science*, 3(4):666–668. Online:https://bit.ly/3Tl5xQq.

Ahmed, N., Razaq, M., and Alam, H. (2016). Response of french bean cultivars to plant spacing under agroclimatic condition of baffa. *Journal of Northeast Agricultural University (English Edition)*, 23(1):16–19. Online:https://bit.ly/3DOSEIx.

Aisawi, K., Reynolds, M., Singh, R., and Foulkes, M. (2015). The physiological basis of the genetic progress in yield potential of cimmyt spring wheat cultivars from 1966 to 2009. *Crop Science*, 55(4):1749–1764. Online:https://bit.ly/3fN1JcW.

Andrade, F. and Abbate, P. (2005). Response of maize and soybean to variability in stand uniformity. *Agronomy Journal*, 97(4):1263–1269. Online:https://bit.ly/3zWdMf2.

Bennett, J., Adams, M., and Burga, C. (1977). Pod yield component variation and intercorrelation in phaseolus vulgaris l. as affected by planting density 1. *Crop science*, 17(1):73–75. Online:https://bit.ly/3UnlczR.

Boada, R. and Espinosa, J. (2016). Factores que limitan el potencial de rendimiento del maíz de polinización abierta en campos de pequeños productores de la sierra de ecuador. *Siembra*, 3(1):67–82. Online:https://n9.cl/odt9v.

Bonelli, L., Cerrudo, A., Pico, L. B., Di Matteo, J., Monzon, J., Rizzalli, R., and Andrade, F. (2020). Does the photo-thermal environment limit post-flowering maize growth? *Field Crops Research*, 252:107805. Online:https://bit.ly/3zYfsVf.

Bustamante, D. (2017). Escenario de cambio climático a nivel de subcuencas hidrográficas para el año 2050 de la provincia de chimborazo-ecuador. *La Granja. Revista de Ciencias de la Vida*, 26(2):15–27. Online:https://bit.ly/3FZEC9G.

Calero-Hurtado, A., Castillo, Y., Quintero, E., Pérez, Y., and Olivera, D. (2018). Efecto de cuatro densidades de siembra en el rendimiento agrícola del frijol común (phaseolus vulgaris l.). *Revista de la Facultad de Ciencias*, 7(1):88–100. Online:https://bit.ly/3NOmh1g.

Castillo, F., Vásquez, S., and Calderini, D. (2017). Does the pre-flowering period determine the potential grain weight of sunflower? *Field Crops Research*, 212:23–33. Online:https://bit.ly/3UE1PlR.

Celmeli, T., Sari, H., Canci, H., Sari, D., Adak, A., Eker, T., and Toker, C. (2018). The nutritional content of common bean (phaseolus vulgaris l.) landraces in comparison to modern varieties. *Agronomy*, 8(9):166. Online:https://bit.ly/3EfPtLq.

De Bruin, J. and Pedersen, P. (2009). New and old soybean cultivar responses to plant density and intercepted light. *Crop science*, 49(6):2225–2232. Online:https://n9.cl/chfvs.

Egli, D. (1988). Plant density and soybean yield. *Crop Science*, 28(6):977–981. Online:https://bit.ly/3TneBUK.

Escalante-Estrada, J., Rodríguez-González, M., and Escalante-Estrada, Y. (2015). Nitrógeno, distancia entre surcos, rendimiento y productividad del agua en dos cultivares de frijol. *Bioagro*, 27(2):75–82. Online:https://n9.cl/p9iqk.

FAOSTAT (2019). Producción agrícola. faostat website. online:https://bit.ly/3g1oFmG. FAOSTAT. Online:https://bit.ly/3g1oFmG.

Fernández de Córdova, F., Gepts, P., and López, M. (1986). *Etapas de desarrollo de la planta de fríjol común (Phaseolus vulgaris L.)*. Centro Internacional de Agricultura Tropical.

Foulkes, M., Slafer, G., Davies, W., Berry, P., Sylvester-Bradley, R., Martre, P., Calderini, D., Griffiths, S., and Reynolds, M. (2011). Raising yield potential of wheat. iii. optimizing partitioning to grain while maintaining lodging resistance. *Journal of experimental botany*, 62(2):469–486. Online:https://bit.ly/3WPPNaX.

Gabisa, M., Ejara, E., and Misgana, Z. (2017). Effect of phosphous application and plant density on yield and yield components of haricot bean (phaseolus vulgaris l.) at yabello southern ethiopia. *International Journal of Scientific Engineering and Applied Science*, 3(3):207–2019. Online:https://bit.ly/324uPKA.

Ghobadi, M., Bakhshandeh, M., Fathi, G., Gharineh, M., Alami-Said, K., Naderi, A., and Ghobadi, M. (2006). Short and long periods of water

stress during different growth stages of canola (brassica napus l.): effect on yield, yield components, seed oil and protein contents. *Journal of Agronomy*, 5(2):336–341. Online:https://scialert.net/abstract/?doi=ja.2006.336.341.

Goyes, D. (2014). Evaluación de la aclimatación de 10 cultivares de fréjol arbustivo (phaseolus vulgaris l), a campo abierto en pisin, cantón riobamba, provincia de chimborazo. Master's thesis, Escuela Superior Politécnica de Chimborazo.

Hadi, H., Ghassemi-Golezani, K., Khoei, F., Valizadeh, M., and Shakiba, M. (2006). Response of common bean (phaseolus vulgaris) to different levels of shade. *Journal of Agronomy*, 5(4):595–599. Online:https://bit.ly/3d8MbvY.

Kruk, B. and Satorre, E. (2003). *Producción de cultivos de granos. Bases funcionales para su manejo*, chapter Densidad y arreglo espacial del cultivo, pages 279–318. Universidad de Buenos Aires.

Labra, M., Struik, P., Evers, J., and Calderini, D. (2017). Plasticity of seed weight compensates reductions in seed number of oilseed rape in response to shading at flowering. *European Journal of Agronomy*, 84:113–124. Online:https://bit.ly/3DP50Ax.

Lake, L., Godoy-Kutchartt, D., Calderini, D., Verrell, A., and Sadras, V. (2019). Yield determination and the critical period of faba bean (vicia faba l.). *Field Crops Research*, 241:107575. Online:https://bit.ly/3DZjOg4.

Luo, Q. (2011). Temperature thresholds and crop production: a review. *Climatic change. Online:https://bit.ly/3hBpXHS*, 109(3):583–598.

Mason, S., Kathol, D., Eskridge, K., and Galusha, T. (2008). Yield increase has been more rapid for maize than for grain sorghum. *Crop Science*, 48(4):1560–1568. Online:https://bit.ly/3WSmggT.

Mondo, V. and Nascente, A. (2018). Produtividade do feijão-comum afetado por população de plantas. *Agrarian*, 11(39):89–94. Online:https://bit.ly/3DULMcN.

Ngouajio, M., Foko, J., and Fouejio, D. (1997). The critical period of weed control in common bean (phaseolus vulgaris l.) in cameroon. *Crop Protection*, 16(2):127–133. Online:https://bit.ly/3DW7UmX.

Osuna, E., Reyes-Muro, L., Padilla-Ramírez, J., and Martínez-Gamiño, M. (2012). Rendimiento de frijol pinto saltillo en altas densidades de población bajo temporal. *Revista mexicana de ciencias agrícolas*, 3(7):1389–1400. Online:https://bit.ly/3A4mQOY.

Parreira, M., Alves, P., and Peñaherrera-Colina, L. (2011). Influencia de las malezas sobre el cultivo de frijol en función de espaciamiento y de la densidad de plantas. *Planta Daninha*, 29:761–769. Online:https://bit.ly/3TrdcwC.

Peltonen-Sainio, P., Kangas, A., Salo, Y., and Jauhiainen, L. (2007). Grain number dominates grain weight in temperate cereal yield determination: evidence based on 30 years of multi-location trials. *Field Crops Research*, 100(2-3):179–188. Online:https://bit.ly/3hy2lUo.

Pereira, H., Melo, L. C., Alvares, R., de Cássia Silva, F., and de Faria, L. (2017). Genetic, environmental and genotype x environment interaction effects on the common bean grain yield and commercial quality. *Semina: Ciências Agrárias*, 38(3):1241–1250. Online:https://bit.ly/3A5vz3v.

Puente, H. (2009). Efecto de la densidad de siembra en el sistema de hileras pares en el rendimiento del frijol (phaseolud vulgaris l.) variedad red kidney en condiciones de tingo maría. Master's thesis, Universidad Nacional Agraria de la Selva.

Reynolds, M., Atkin, O.and Bennett, M., Cooper, M., Dodd, I., Foulkes, M., Frohberg, C., Hammer, G., Henderson, I., and Huang, B. (2021). Addressing research bottlenecks to crop productivity. *Trends in Plant Science*, 26(6):607–630. Online:https://bit.ly/3TrX65K.

Sadras, V. and Denison, R. (2009). Do plant parts compete for resources? an evolutionary viewpoint. *New Phytologist*, 183(3):565–574. Online:https://bit.ly/3hA6IOz.

Sadras, V. and Lawson, C. (2011). Genetic gain in yield and associated changes in phenotype, trait plasticity and competitive ability of south australian wheat varieties released between 1958 and 2007. *Crop and Pasture Science*, 62(7):533–549. Online:https://bit.ly/3G6dBkT.

Sadras, V. and Slafer, G. (2012). Environmental modulation of yield components in cereals: Heritabilities reveal a hierarchy of phenotypic plasticities. *Field crops research*, 127:215–224. Online:https://bit.ly/3TqJDew.

Sadras, V. O. (2007). Evolutionary aspects of the trade-off between seed size and number in crops. *Field Crops Research*, 100(2-3):125–138. Online:https://bit.ly/3hwWEpM.

Serrago, R., Alzueta, I., Savin, R., and Slafer, G. (2013). Understanding grain yield responses to source-sink ratios during grain filling in wheat and barley under contrasting environments. *Field Crops Research*, 150:42–51. Online:https://bit.ly/3G5ZPyN.

Sistema de Información Publica Agropecuaria de Ecuador (2018). Boletín situacional fréjol tierno y seco. Sistema de Información Publica Agropecuaria de Ecuador. Online:https://bit.ly/3s5rKUP0.

Slafer, G. and Rawson, H. (1994). Sensitivity of wheat phasic development to major environmental factors: a re-examination of some assumptions made by physiologists and modellers. *Functional Plant Biology*, 21(4):393–426. Online:https://bit.ly/3TljNss.

Slafer, G., Savin, R., and Sadras, V. (2014). Coarse and fine regulation of wheat yield components in response to genotype and environment. *Field Crops Research*, 157:71–83. Online:https://bit.ly/3ElW476.

Soratto, R., Catuchi, T., Souza, E., and Nantes Garcia, J. L. (2017). Plant density and nitrogen fertilization on common bean nutrition and yield. *Revista caatinga*, 30:670–678.

Valarezo, O., Cañarte, E., Navarrete, B., Guerrero, J., and Arias, B. (2008). Diagnóstico de la "mosca blanca" en ecuador. *La Granja. Revista de Ciencias de la Vida*, 7(1):13–20. Online:https://bit.ly/3Ek4XhB.

Vásquez, S., Mestanza, C., and Riegel, R. (2015). Caracterización de secuencias de los genes ahas y psba relacionados con resistencias a herbicidas en lupinus albus l. *Agro Sur*, 43(1):31–40. Online:https://bit.ly/3tqeTzC.

Véliz, D., Franco, L., Mestanza, C., Vásconez, G., Vásquez, S., and Pinargote, J. (2021a). Aplicación de sistemas de nitrógeno en el rendimiento de quinua adaptada a sistemas tecnológicos. *Revista Ibérica de Sistemas e Tecnologias de Informação*, (E44):119–131. Online:https://bit.ly/3WRcE67.

Véliz, D., Pinochet, D., Mestanza, C., Vera, J., Vásque, S., and Pinargote, J. (2021b). Phosphorus availability and solar radiation efficiency in carrot (daucus carota l.) cultivation in volcanic soils. *Revista Científica Interdisciplinaria Investigación y Saberes*, 11(2):44–65. Online:https://bit.ly/3pZ1Djt.