FORMATIVE RESEARCH IN BIOTECHNOLOGY: A CRITICAL REVIEW.

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Resumen.

Biotechnology is a multidisciplinary field that combines fundamental sciences such as chemistry, biology, and physics, generating technological innovations capable of artificially modifying living organisms and giving rise to the concept of "biotechnoscience." This integrative approach has potential impacts on areas such as social welfare and economic development. However, its inclusion in higher education has been limited, reflecting a limited presence in classrooms and scarce research on specific pedagogical methods for its teaching. This article presents a critical review of formative research in biotechnology, analyzing various didactic and methodological strategies implemented in higher education programs. Through a systematic literature review with a qualitative approach, the most effective methodologies for developing scientific and technical competencies in university students were identified. The results underscore the importance of restructuring educational experiences by integrating advanced tools such as bioinformatics and implementing innovative methodologies in laboratories. Formative research in biotechnology enables students to apply theoretical knowledge in practical contexts, developing essential technical skills and fostering critical and innovative thinking. However, the effectiveness of these methodologies faces significant barriers, including limited access to optimal resources, traditional approaches in laboratories, and insufficient research training for faculty and students. Therefore, it is crucial to promote a more deeply rooted research culture in higher education institutions, thus ensuring comprehensive training that accurately addresses the current and future demands of the biotechnology field.

Keywords: biotechnology, didactics, formative research, teaching strategies, higher education.

Abstract.

La biotecnología es un campo multidisciplinario que combina ciencias fundamentales como la química, la biología y la física, generando innovaciones tecnológicas capaces de modificar artificialmente organismos vivos, y generando el concepto denominado "biotecnociencia". Este enfoque integrador tiene impactos potenciales en áreas como el bienestar social y el desarrollo económico. No obstante, su inclusión en la educación superior ha sido limitada, lo que refleja una limitada representación en aulas y una escasa investigación en métodos pedagógicos específicos para su enseñanza. Este artículo realiza una revisión crítica sobre la investigación formativa en biotecnología, analizando diversas estrategias didácticas y metodológicas implementadas en programas de educación superior. Mediante una revisión sistemática de literatura con enfoque cualitativo, se identificaron las metodologías más eficaces para desarrollar competencias científicas y técnicas en estudiantes universitarios. Los resultados subrayan la importancia de reestructurar las experiencias educativas mediante la integración de herramientas avanzadas como la bioinformática y la implementación de metodologías innovadoras en laboratorios. La investigación formativa en biotecnología facilita que los estudiantes empleen conocimientos teóricos en contextos prácticos, desarrollando habilidades técnicas imprescindibles y fomentando el pensamiento crítico e innovador. Sin embargo, la efectividad de estas metodologías se enfrenta a barreras destacables, incluyendo limitaciones en el acceso a recursos óptimos, enfoques tradicionales en los laboratorios, y formación insuficiente en investigación para docentes y estudiantes. Por tanto, resulta fundamental promover una cultura investigativa más arraigada en las instituciones educativas superiores, garantizando así una formación integral que responda de forma certera a las demandas actuales y futuras del campo biotecnológico.

INVESTIGACIÓN FORMATIVA EN BIOTECNOLOGÍA: UNA REVISIÓN CRÍTICA.

Palabras clave: Biotecnología, didáctica, investigación formativa, estrategias didácticas, educación superior.

I. INTRODUCTION.

Biotechnology is a multidisciplinary field that integrates sciences such as chemistry, biology and physics, allowing the understanding of living phenomena, in turn, offering tools and technological advances that allow artificially modifying living organisms. In this sense, the convergence of sciences and technologies has given rise to the concept of "biotechnology", where scientific research and technological applications are intertwined without clear distinctions between knowledge and application (Espinel-Barrero & Valbuena-Ussa, 2018; Roa Acosta & Valbuena Ussa, 2013). This development has potential impacts in areas such as social and economic well-being, which underlines the importance of promoting its study and teaching (Abuqamar et al., 2015).

Although biotechnology is an important and rapidly advancing field, it has not been a common topic in science education. It is underrepresented in curricula and classrooms, and has not been comprehensively studied by researchers in science didactics (Nordqvist & Aronsson, 2019; Orhan & Sahin, 2018). In addition, the circulation of ideas and practices regarding its teaching is still incipient, although growing, and the proposals for how to teach this content are not fully defined (Marcelino & Marques, 2017). In this context, didactics, as a mediating activity between the teacher and his students, denotes a primordial role. Biotechnology teachers must continually update their knowledge in the field to strengthen fundamental concepts in the classroom, using innovative strategies that address current teaching needs (Bernardes, 2019; Uve et al., 2022). By covering different options and areas of biotechnological knowledge, it is possible to arouse the interest and motivation of higher education students.

The figure of the educator in higher education is crucial to achieve a real leap in quality in the education of a country, being the true strategy to positively modify society. Therefore, it is essential to create didactic and pedagogical approaches that allow conditions for practice to achieve a current and well-structured dialogue. Within the field of natural sciences, and specifically in biotechnology, the implementation of various learning strategies is key for students to develop practical skills and acquire meaningful learning (Cortes et al., 2017).

At the university level, formative research in biotechnology allows the training of students as competent researchers and professionals in a field that is constantly evolving. This research modality gives students the opportunity to use their theoretical knowledge, acquire practical skills and participate in relevant projects, preparing them for future scientific and technological demands (Crane & Page, 2022). In addition, it encourages the development of technical skills and fundamental scientific principles necessary for innovation (Baranovskyy & Baranovska, 2023). However, limited accessibility to authentic research experiences and the traditional approach of laboratories hinder or inhibit the development of critical thinking and innovation (Chaari et al., 2020).

In addition to this, formative research faces several obstacles that limit its effectiveness, such as the lack of adequate educational methodologies, limited access to necessary resources and insufficient training in and for research, which implies that both teachers and students may not be adequately prepared to carry out high-quality research (Restrepo, 2007). Among the main problems are the limited development of research skills and the lack of interdisciplinary integration, which reduces the understanding of the impact of technological advances (Nordqvist & Aronsson, 2019). The research culture, which encompasses values, attitudes, techniques and methods associated with research activity, is not sufficiently entrenched in all institutions, affecting the ability to promote and sustain high-quality research (Restrepo, 2007).

In this sense, a restructuring of educational experiences in biotechnology is necessary, incorporating advanced tools such as bioinformatics and innovative methodologies in laboratories (Chaari et al., 2020). This will not only contribute to theoretical learning but also allow students to apply this knowledge in real environments, developing technical and critical thinking skills essential for scientific careers (Kaufman, 2020). Therefore, to approach this review, a qualitative approach was adopted through a systematic review of the literature, integrating hermeneutical analyses that allowed a deep understanding of the didactic strategies of biotechnology. The objective of this review article is to synthesize the didactic and methodological strategies of formative research applied in undergraduate biotechnology programs, in order to identify those that have proven to be most effective in the formation of scientific and technical competencies.

II. METHODOLOGY.

This review was carried out from a qualitative paradigm of an inductive nature, which allows flexibility in data collection. In this paradigm, the collection and analysis of qualitative data are dynamically integrated, reflecting a constant interaction between both processes (Hernández-

Sampieri et al., 2014). In addition, a hermeneutical approach was adopted, framed within the qualitative paradigm, which facilitates a deep understanding of the studied phenomena through the interpretation of texts and discourses. This approach emphasizes the historical, cultural and social context, recognizing that knowledge is built through interpretation and dialogue, rather than being a set of fixed and absolutely objective facts (Franco's Finol & Vera Solórzano, 2020; Rojas Arango & Arroyo Ortega, 2021).

This article is a systematic review, understood as an integrative study, of an observational and retrospective nature, which uses secondary data to combine research focused on a common question (Beltran, 2005). This type of review provides a rational synthesis of basic research and exceeds the standards of a narrative review, since it applies rigorous standards to secondary research, similar to those used in primary research studies (Beltrán, 2005; Moreno et al., 2018). In this way, the aim is to consolidate the existing evidence, identify areas for improvement and establish recommendations based on solid data, in order to optimize the didactic and methodological strategies of formative research in biotechnology and related disciplines.

For the selection of the articles that support the documentary analysis of this research, various bibliographic databases were used, focusing on high-impact scientific journals. The platforms used included Google Scholar, ScienceDirect and Scopus, each queried with a specific set of keywords designed to capture the essence of biotechnology research at the undergraduate level. The search terms were "biotechnology undergraduate research "for Google Scholar, while on ScienceDirect it was expanded with terms such as" biotechnology research education". In Scopus, the search strategy was structured by combining Boolean operators: "biotechnology" and "research" AND "undergraduate".

A total of 103 documents were identified in Scopus, limiting the search to the period between 2019 and 2024. This time limitation made it possible to focus the analysis on the most recent and relevant research. The selection was restricted to articles, book chapters and conference papers, in order to cover a wide range of textual formats rich in content and scientific analysis. Studies from various countries were included to obtain an international perspective, without being limited to a specific geographical context. In addition, only those studies that presented empirical results and concrete evidence related to the teaching of biotechnology and related areas in higher education were considered.

Advanced platforms supported with Artificial Intelligence (AI), such as SciSpace, Elicit and Consensus, were also used in their free versions. These tools facilitated the obtaining of clear and concise explanations provided by the AI from each article analyzed, as well as the discovery of a network of interconnected and relevant articles, enriching the depth and scope of documentary research.

The studies were subjected to a manual selection process. In a first stage, the titles, abstracts and conclusions were examined to eliminate the studies that did not meet the inclusion criteria. Subsequently, a review of the full text of the studies was carried out, ensuring their relevance. For the systematic extraction of data from the included studies, a documentary analysis matrix was used.

The documentary analysis matrix enabled comparison and contrast of the findings from the included studies, thereby identifying common patterns, discrepancies, and gaps in the literature. From this comparison, the information was synthesized qualitatively, highlighting emerging issues, relevant trends, and areas that require further research.

The documentary analysis matrix covered a total of 10 meticulously selected articles. This analysis covered various dimensions, from a Thematic Analysis that includes the Title, Topics, Subtopics and Type of population, to a Bibliometric Analysis that details the Textual Typology, APA Reference, DOI or URL, Year, Keywords, Database, Language and Country, along with a summary, results and conclusions of each document. In addition, a Methodological Analysis was carried out, focused on the Paradigm and Approach, Study Design, Procedures, Population Sample, Instruments, and the use of Information and Communication Technologies (ICT) used, including statistical analysis software and equipment. Finally, Notes, Observations and Comments relevant to each article were included. The results present a summary of the documentary analysis matrix, highlighting the most representative or most interesting columns for the reader.

III. RESULTS.

In the systematic review on formative research in biotechnology in undergraduate studies, various sources highlight the application of innovative methods, among which are Project-Based Learning (PBL), Course-Based Undergraduate Research Experiences (CUREs), Problem-

Based Learning (PBL) and other strategies focused on active or inquiry-based learning.

A. Project-Based Learning (PBL).

Ocampo-López et al. (2019) highlight how PBL integrates the academic curriculum with research groups, encouraging the creation of technologies with commercialization potential. Students actively participate in solving real problems, promoting technological and social innovation. Balasubramanian & Chatterjee (2022) apply PBL in bioinformatics, where students develop a workflow for therapeutic applications using open-source tools. This type of learning allows them to acquire technical skills in the prediction and analysis of bioinformatics data.

Chaari et al. (2020) describe a PBL-based course where students purify and characterize enzymes, integrating experimental techniques and bioinformatics tools, which strengthens their ability to interpret results and solve laboratory problems. Rendon-Castrillón et al. (2023) implement PBL supported by green chemistry and sustainability, promoting the solution of real problems with a guide to circular economy. Students develop time management, experimentation and teamwork skills, linking biotechnology with sustainability.

B. Course-Based Research Experiences (CUREs).

Mintzes & Walter (2020) emphasize that CUREs allow students to participate in real research with unknown results, promoting self-efficacy and identification as scientists. This increases their persistence in STEM disciplines (Science, Technology, Engineering, and Mathematics) and is inclusive of students from different social classes. Roberts & Shell (2023) describe how students work on biotechnology projects using advanced technologies such as CRISPRI and gene expression analysis. These activities promote autonomy and the development of collaborative skills, contributing to ongoing research.

Pieczynski et al. (2019) apply CURE in genetics courses using CRISPR-Cas9 technology, where students design and test genetic tools, which encourages decision making and problem solving, improving their research skills. Rulfs et al. (2022) integrate students into initiatives such as the "Tiny Earth Initiative" and "SEA-PHAGES", where they look for antibiotics and bacteriophages. These experiences promote a sense of belonging in the projects and improve technical and scientific skills. Shelby (2019) implements CURE in biochemistry, where students investigate protein-protein interactions. This allows active participation and the development of key experimental skills to be encouraged through guided inquiry and peer mentoring.

Kaufman (2020) introduces a CURE approach in bioinformatics, where students perform genomic analyses using computational tools. Active research and collaboration among students are strengthened, improving their technical skills and allowing results to be generated for publication. Gao & Guo (2023) apply CUREs in bioinformatics, teaching students' data analysis through R programming and the use of public genomic databases. Through research projects, students acquire competencies in data analysis and publish their results, which strengthens their preparation for future research.
Johnson et al. (2022) highlight the use of CUREs in biotechnology and synthetic biology, where students design and assemble genetic devices, in this way, scientific communication, problem solving and critical thinking are improved, strengthening their sense of belonging to a scientific community. Peyton & Skorupa (2021) apply CUREs for students to investigate microorganisms that biodegrade plastics. These activities allow them to develop skills in data analysis and collaborative work, preparing them for future careers in biotechnology and microbiology. Balke et al. (2021) implement courses in biotechnology with two modalities: classroom research, which develops critical thinking and teamwork, and mentored research, where students work on long-term projects, strengthening their self-efficacy and experimental competencies.

C. Inquiry-Based Learning.

Desai et al. (2019) propose an approach that combines practical activities with the use of technological tools, such as Minitab, for data analysis and the writing of scientific articles. This allows students to apply theoretical concepts to practical situations, improving their understanding of research methodologies. Williams et al. (2020) implement a cell-free protein synthesis system (CFPS), which allows students to manipulate biological machinery. This hands-on strategy encourages active learning and enhances their understanding of essential biochemical processes, providing an inquiry-based classroom experience.

D. Problem-Based Learning (PBL).
(Yani & Adiansyah, 2019) designed a PBL module, validated and tested it, finding that this module

significantly improved critical thinking and learning outcomes in the cognitive area. The students showed high motivation, greater participation in problem solving and a better understanding of biotechnological concepts. Shan et al. (2023) implement a laboratory course focused on the study of ageing using Drosophila melanogaster. Students gain practical experience in laboratory techniques and data analysis, improving their confidence and understanding of scientific research. Tikhomirova (2020) uses PBL in group projects and situational analysis, where students solve problems related to biotechnology. This approach promotes autonomy and creativity by applying theoretical knowledge in simulated professional situations and by developing technical and transversal skills.

E. Research-Based Learning (ABI).

Arjona et al. (2019) highlight that the ABI enabled students to apply theoretical concepts to real research, improving their skills in research, critical thinking and problem-solving. The students involved performed better than their peers and showed greater motivation towards learning. Bickford et al. (2020) found that STEM students who participated in research also had superior academic performance in various subjects. In addition, he observed that students with an interest in research already showed better performance before getting involved, suggesting that the ABI attracts students with a higher academic motivation.

F. Active Learning.

Basu (2023) presents an introductory course on research methods in biotechnology, where students participate in group activities and apply basic laboratory techniques. This approach encourages critical analysis and the connection between science and society, promoting the participation of underrepresented minorities in STEM. Crane & Page (2022) implement a laboratory module that teaches molecular biology techniques, such as template-free PCR and RT-PCR, to detect SARS-CoV-2 RNA in environmental samples. Students design and execute experiments based on scientific protocols, applying theoretical knowledge in a relevant and practical context. Pao et al. (2021) apply an active learning approach in bioinformatics, where students study oral microbial communities through sample collection, PCR analysis and sequencing. The course culminates in the presentation of results in poster format, integrating genetics, microbiology and bioinformatics analysis in a real experience. Ripoll et al. (2023) highlight the use of active learning through face-to-face projects that combine learning sequences based on the use of ICT and problem-solving, promoting learning by discovery and collaborative work.

G. Other innovative strategies.

Iannotta et al. (2024) describe the narrative approach and its integration into real-world scenarios with a longitudinal perspective. It includes the incorporation of practical techniques within a narrative context that simulates important social challenges, such as the development of vaccines and the identification of pathogens. Through the use of narrative in teaching, the retention and deep understanding of complicated concepts are favoured, which motivates students and improves the educational experience. Thus, the application of laboratory techniques in interconnected problems is encouraged, which helps students to reveal the social importance of their technical skills, increasing their interest in applied sciences and their career prospects.

On the other hand, Ningrum et al. (2020) focus on the development of innovative educational materials such as research-based textbooks. The area of bioinformatics is used to link science and technology in a contextual way, allowing students to understand biotechnology concepts through practical examples. The development methodology of "Dick and Carey" covers stages such as the analysis of educational needs, the development of learning strategies, and formative and summative assessment. Tests and validations with experts and students indicate that this approach improves learning outcomes.

In Table 1, at the end of this article, the documentary analysis matrix is included, in which ten meticulously selected articles are reported according to the criteria described in the methodology of this research.

IV. DISCUSSION.

The documentary analysis matrix for the description of recent initiatives and projects in the field of biotechnology research highlights a wide diversity of approaches, themes and methodologies used to improve both the educational experience and the research advances in the field. The analyzed projects highlight the use of course-based undergraduate research experiences (CURE, for its acronym in English), which integrate active and technological methodologies for practical and applied learning. These experiences encourage students' participation in research, increasing their understanding and skills in critical scientific areas (Chaari et al., 2020; Crane & Page, 2022; Kaufman, 2020; Mintzes & Walter, 2020).

The research covers areas such as biotechnology engineering, molecular biology, green chemistry and biochemistry, as well as sub-topics such as enzyme inhibition, molecular modelling, research pedagogy, bioinformatics analysis and synthetic biology. The target population of these studies varies from undergraduate students of different years and disciplines to master's students, reflecting the transversality and importance of biotechnology in academic education at different levels (Desai et al., 2019; Rendón-Castrillón et al., 2023).

The bibliometric and methodological analysis indicates a preference for empirical and mixed hermeneutical approaches, highlighting the combination of qualitative and quantitative techniques to deepen learning and research. A variety of techniques are employed for data collection and analysis, ranging from surveys and institutional data analysis to software tools specialized in bioinformatics, statistical and intellectual property analysis (Shan et al., 2023; Tikhomirova, 2020).

The evidence and evaluation of the studies show a recognition of the contribution of ICT to teaching and research in biotechnology. Tools such as Expasy, Autodock Vina, OASIS, Minitab, and data analysis and plagiarism software prove to be useful in education and research practice. These tools allow performing comparative structural analysis of proteins and molecular docking to bibliometric and statistical analyses (Chaari et al., 2020; Crane & Page, 2022).

Finally, the projects and experiences reported illustrate the effectiveness of CURES, PBL, and other research-based methodologies used to strengthen problem solving, technical knowledge, autonomous learning, effective communication and critical thinking, preparing students to face future challenges with a solid scientific and technological base.

V. CONCLUSIONS.

The findings of this systematic review highlight the importance of integrating innovative methodologies such as Project-Based Learning (PBL), Course-Based Research Experiences (CUREs) and Problem-based Learning (PBL) into undergraduate biotechnology programs. These strategies not only promote active and practical learning, but also enhance the development of technical skills, critical thinking and problem-solving skills among students, fundamental aspects for their future scientific career. The implementation of approaches such as PBL has proven its effectiveness by linking academic content with real applications, allowing students to participate in the creation of technologies with potential impact on society and the economy.

On the other hand, CUREs have been fundamental in the promotion of self-efficacy and the identification of students with the role of researcher, increasing their persistence in STEM disciplines. This approach has also proven to be inclusive, allowing the participation of students from different social contexts and academic levels, which reinforces diversity in the scientific field. In addition, the incorporation of advanced technological tools, such as bioinformatics platforms and molecular and statistical analysis software, has facilitated autonomous and collaborative learning, allowing students to face complex scientific problems with greater confidence.

However, the results also reveal some challenges that limit the effectiveness of these methodologies, such as the lack of access to adequate resources and the scarce research training of both teachers and students. This scenario highlights the importance of promoting the research culture in universities through a greater incorporation of ICT and greater training of educators in research-based teaching strategies.

Finally, the relevance of restructuring educational experiences in biotechnology to include more integrative and transversal approaches that allow meaningful learning is highlighted. The combination of qualitative and quantitative methods in the analyzed studies shows that, when applied correctly, these strategies not only improve students' technical understanding but also encourage a more active participation in research, better preparing them for the scientific and technological challenges of the future.

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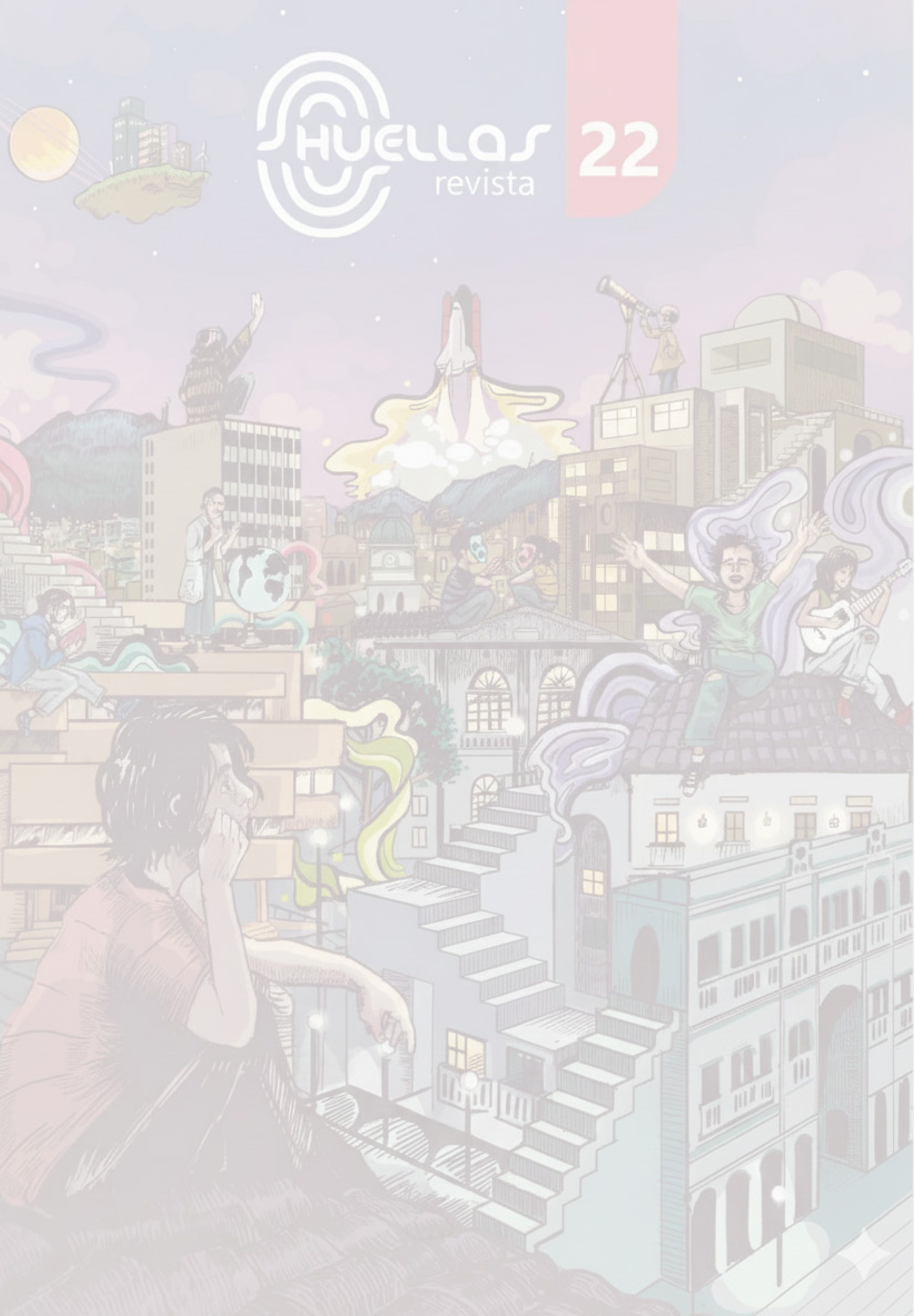

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