Optics Learning Beyond the Classroom: Non-Formal STEM Strategies for Rural Students

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Abstract

Evidence on non-formal optics education in rural contexts remains scarce (<10%), revealing an equity gap in access to meaningful STEM learning. We conducted a PRISMA-guided systematic review of 38 empirical studies with school-age learners (5–18). Four research questions examined: (PI1) effects on conceptual understanding compared with formal instruction or pre–post baselines; (PI2) the added value of news articles and interactive visualizations for transfer, curiosity/motivation, and self-efficacy; (PI3) pedagogical features linked to higher learning gains; and (PI4) contextual differences across rural vs. urban and Latin America vs. other regions. Searches in Scopus, Web of Science (Core Collection), and ERIC (1990–2025), with Elicit as supplementary discovery, included experimental, quasi-experimental, and pre–post designs reporting validated optics outcomes (reflection, refraction, image formation, wave optics). Studies were conducted primarily in non-formal settings, museums, university labs, after-school programs, camps, and in school-based outreach/museum-integrated activities. Results show consistent gains in conceptual understanding; larger effects occur when perceived authenticity, guided inquiry, and sustained hands-on activity converge, supported by low-cost materials and simulations. A small subset indicates that news-based and interactive visual resources enhance transfer, curiosity/motivation, and self-efficacy. We conclude with a STEM-informed, culturally responsive workshop model for rural learners and propose a research agenda emphasizing rural implementations, delayed retention measures, standardized instruments, and sociocultural moderators to translate non-formal optics learning into durable, context-relevant outcomes.

Keywords: Optics Education, Non-Formal Learning, Conceptual Understanding, STEM.

Resumen

La evidencia sobre la educación óptica no formal en contextos rurales sigue siendo escasa (<10%), lo que revela una brecha de equidad en el acceso a un aprendizaje significativo en STEM. Realizamos una revisión sistemática guiada por PRISMA de 38 estudios empíricos con estudiantes en edad escolar (5-18 años). Cuatro preguntas de investigación examinaron: (PI1) efectos en la comprensión conceptual en comparación con la instrucción formal o líneas base pre-post; (PI2) el valor añadido de los artículos periodísticos y las visualizaciones interactivas para la transferencia, la curiosidad/motivación y la autoeficacia; (PI3) características pedagógicas vinculadas a mayores logros de aprendizaje; y (PI4) diferencias contextuales entre zonas rurales y urbanas, y entre América Latina y otras regiones. Las búsquedas en Scopus, Web of Science (Colección Principal) y ERIC (1990-2025), con Elicit como descubrimiento complementario, incluyeron diseños experimentales, cuasiexperimentales y pre-post que reportaron resultados ópticos validados (reflexión, refracción, formación de imágenes, óptica ondulatoria). Los estudios se realizaron principalmente en entornos no formales, museos, laboratorios universitarios, programas extraescolares, campamentos y actividades de divulgación escolar integradas en museos. Los resultados muestran mejoras consistentes en la comprensión conceptual; los efectos más significativos se producen cuando convergen la autenticidad percibida, la indagación guiada y la actividad práctica sostenida, con el apoyo de materiales y simulaciones de bajo costo. Un pequeño subconjunto indica que los recursos visuales interactivos y basados en noticias mejoran la transferencia, la curiosidad/motivación y la autoeficacia. Concluimos con un modelo de taller basado en STEM y culturalmente receptivo para estudiantes rurales y proponemos una agenda de investigación que enfatiza las implementaciones rurales, las medidas de retención diferida, los instrumentos estandarizados y los moderadores socioculturales para traducir el aprendizaje no formal de óptica en resultados duraderos y relevantes para el contexto.

Palabras clave: Educación en Óptica, Aprendizaje No Formal, Comprensión Conceptual, STEM.

I. INTRODUCTION

Non-formal learning environments-such as university laboratories, summer camps, school-based outreach programs, and extracurricular courses-provide students with hands-on experimentation and authentic tasks when studying optical principles [1]. These settings have been recognized as essential to fostering meaningful learning experiences, as they immerse participants in concrete, active engagement that promotes deeper and longer-lasting conceptual understanding.

Beyond content acquisition, non-formal environments nurture critical competencies such as creative thinking, problem-solving, communication, collaboration, and autonomy, which are vital for both personal development and professional success. One of the key advantages of these contexts is their flexibility, they allow for the adaptation of content, pace, and learning location according to individual needs and interests, thus enhancing learner agency and motivation.

Authentic learning situations offer students opportunities to apply scientific knowledge in real-life contexts. Unlike traditional classroom methods that often rely on abstraction [2, 3], experiential and situated learning can significantly boost both motivation and the development of domain-specific skills [4, 5]. However, the effectiveness of these learning experiences depends heavily on the students' perceived authenticity [6, 7]. If students do not perceive the learning situation as realistic or relevant, the intended cognitive and affective outcomes may not be achieved. Therefore, educators must consider students' subjective perceptions when designing non-formal learning interventions to optimize their educational impact.

In the context of optics education, non-formal environments complement traditional instruction by providing intimate, experiential, and situated learning opportunities. These spaces can enrich students' understanding of complex physical phenomena such as light, reflection, and refraction through observation, manipulation, and inquiry.

This paper presents a PRISMA-guided systematic literature review addressing four research questions (PI1–PI4) on non-formal optics education for school-age learners (5–18), focusing on effects on conceptual understanding, the added value of news articles and interactive visualizations, pedagogical features associated with larger gains, and contextual differences (rural vs. urban; Latin America vs. other regions).

The findings of this systematic review will serve as the empirical foundation for designing a context-responsive science workshop tailored to rural learners. By identifying the most effective pedagogical strategies in non-formal settings-such as authenticity, hands-on inquiry, and contextual relevance-we aim to develop a learning experience that not only addresses students' alternative conceptions of light but also fosters equitable access to scientific knowledge. The review guides both the structure and content of the intervention, ensuring that each activity is grounded in evidence-based practices and aligned with the cognitive and sociocultural characteristics of the target population. Ultimately, this review is not an end, but rather a starting point for a pedagogical design process that aspires to bridge research, outreach, and inclusive science education.

Non-formal educational environments promote the assimilation and appropriation of optical concepts through practical experimentation and problem-solving. Additionally, they provide flexibility and customization in learning, enabling students to progress at their own pace and according to their cognitive abilities. Activities in non-formal settings mirror real-life scientific practices, thereby reinforcing motivation and facilitating the transfer of knowledge in authentic and meaningful contexts. These environments also foster the Zone of Proximal Development through collaboration and guidance from trained educators, emphasizing learning as a social process mediated by interaction with others and with cultural tools. Moreover, engaging with real-life optical phenomena (such as reflection and refraction) in non-formal settings allows students to follow the experiential learning cycle: concrete experience - reflective observation -abstract conceptualization - active application.

Taken together, these elements place the teaching of optics within a constructivist framework-cognitive and experiential in nature-with a social dimension grounded in situated learning.

Considering these considerations, it becomes necessary to explore the theoretical foundations that support learning in non-formal environments, especially those grounded in constructivist, sociocultural, and STEM-based approaches, which offer valuable guidance for designing effective and context-sensitive educational interventions.

II. THEORETICAL FOUNDATION

Grounded in the constructivist and sociocultural perspectives previously discussed, the present study conducted a systematic literature review to examine how non-formal educational interventions support conceptual learning in optics among school-age learners.

Active learning is grounded in educational theories that emphasize the sociocultural and constructivist nature of science learning. Vygotsky's concept of the Zone of Proximal Development (ZPD) [8] highlights that learning is most effective when students engage in guided exploration alongside peers or facilitators. This perspective is particularly relevant in non-formal settings, where dialogic interaction, voluntary participation, and context-sensitive pedagogy foster meaningful learning processes. By situating learners within authentic experiences, these environments encourage the development of conceptual understanding through social mediation, experimentation, and reflection.

Similarly, the theory of situated learning [9], highlights the importance of authentic practices and the context in which learning occurs. In non-formal education, tasks are embedded in real-life situations, allowing students to construct meaning through experience and social participation. This experiential foundation is essential when teaching optics, a domain often perceived as abstract and disconnected from everyday life.

Non-formal education, as conceptualized by Malcolm, Hodkinson and Colley, in reference [10], is not merely a matter of setting, but of pedagogy: it promotes learning that is voluntary, learner-centered, and context-responsive. It allows for the integration of culturally relevant knowledge and flexible pacing, which is critical when working with underserved populations or in rural contexts where access to formal resources is limited.

Moreover, the constructivist paradigm, particularly in science education, advocates for inquiry-based learning, hands-on exploration, and reflection as pillars of meaningful understanding. When students manipulate materials, test ideas, and reflect in community, they are more likely to develop both conceptual understanding and a sense of ownership over scientific knowledge.

Taken together, these theoretical perspectives provide a strong foundation for understanding the value and potential of non-formal optics education, particularly when applied in rural or marginalized contexts where science education must be as inclusive as it is rigorous.

Additionally, the STEM framework (Science, Technology, Engineering, and Mathematics) reinforces constructivist and sociocultural theories by promoting interdisciplinary, problem-centered learning. It encourages students to engage in modeling, prototyping, and testing-practices that not only align with engineering design but also deepen scientific understanding. The integration of STEM into non-formal education is particularly powerful in rural contexts, where learners can investigate locally meaningful phenomena while developing scientific and technological competencies. STEM education strengthens these perspectives by introducing timely, relevant, and accessible materials that foster cognitive and emotional connections to scientific content [11].

Within this teaching approach, the inclusion of learning activities that promote cognitive, procedural and socio-emotional skills become relevant. It has been seen that, for example, integrating information resources such as news and interactive visualizations into science teaching can strengthen students' motivation, curiosity, and knowledge retention [12]. When these resources are adapted to rural or historically underserved contexts, they not only act as bridges between scientific literacy and everyday media, but as Loaiza suggests, they become tools for transforming realities, recognizing in rural territories a fertile space for generating science with cultural relevance, social commitment, and community roots [13, 14].

In reference [15] Martínez and Suárez explored conceptions of light in 10- to 12-year-old children participating in a regional science competition. Through an analysis of their responses, they found that 50% of the children are conceived of light as an entity that moves through space, an idea closer to the scientific view than the traditional conception of light as a source or effect. This research highlights the importance of outreach and informal teaching contexts for identifying and promoting advanced scientific concepts from an early age, even in the absence of systematic instruction. In this case, the competition itself, although structured as an exam, is configured as a scientific outreach activity, by generating a non-school-based space where reflection, contact with physical phenomena, and the exploration of individual explanations are activated. The authors conclude that these experiences contribute to expanding students' empirical range and facilitate more evolved mental frameworks, suggesting that it is possible to improve learning about scientific concepts of light in children through well-designed interventions in informal settings [15].

Sociocultural theories, the constructivist approach, non-formal education pedagogy, and the STEM perspective converge on a common idea: scientific learning can be profound, meaningful, and transformative when it connects with students' realities, is supported by authentic practices, and is promoted in flexible, voluntary, and culturally relevant spaces. This framework enables the design of an optics workshop in rural communities that not only teaches concepts but also empowers children scientifically as epistemic actors within their own territory.

In informal settings, with an emphasis on active approaches and in school populations between 5 and 18 years old. This review allowed us to identify both the most effective pedagogical approaches-such as guided inquiry, contextualization, and situated learning-and the main limitations of existing research, including the limited presence of studies in rural settings, the weak articulation between diagnosis and intervention, and the lack of cultural adaptation in the resources used. The review not only provides a solid empirical basis to support the design of an optics learning activity in informal settings for rural communities but also guides the construction of a pedagogical intervention aligned with principles of equity, contextual relevance, and scientific rigor.

III. METHODOLOGY

This study aims to identify the progress and gaps in educational interventions developed in non-formal settings for optics learning among children and adolescents. It also analyzes the characteristics of their implementation, the most effective strategies, and the pedagogical approaches employed to guide future situated, inclusive, and evidence-based teaching proposals, especially in rural contexts.

The objectives set out in the following review are as follows:

O1. To identify and analyze empirical studies related to the teaching of optics in non-formal environments and their impact on the conceptual understanding of students aged 5 to 18.

O2. To examine the characteristics of educational interventions implemented in these settings to determine which pedagogical strategies are the most effective.

O3. To propose an empirical basis for the design of a science pedagogical intervention, grounded in STEM principles, aimed at rural communities, and aligned with the effective educational practices identified in the review.

TABLE I. Inclusion and exclusion criteria of the review.

Inclusion criteria	Exclusion criteria
Examines learning in non-formal educational settings (outdoor learning environments, after-school programs)	Examinations learning in formal educational settings
Measures specific learning outcomes related to conceptual understanding, skill development, or knowledge retention	Does not measure specific learning outcomes related to conceptual understanding, skill development, or knowledge retention
Examine and describe specific pedagogical approaches or teaching methods	Does not examine or describe specific pedagogical approaches or teaching methods
Employ qualitative, quantitative, or mixed methods approaches and provide empirical evidence	Does not employ qualitative, quantitative, or mixed methods approaches, nor provide empirical evidence
It focuses specifically on education in optics (including geometric optics, physical optics, or applied optics) rather than general science education	It focuses specifically on general science education
Presence of a comparison group exposed to formal classroom instruction	Absence of comparison group exposed
Was written in English or Spanish	Was written in other language
Participant age between 5 and 18 years old	Age of participants outside the range of 5 to 18 years
It was published between 1990 and 2025	It was published outside the time range of 1990 to 2025
Presence of a comparator: Formal classroom instruction or a pre-post baseline within the same sample.	No outcome comparison (e.g., single-group cross-sectional without pre/post) or insufficient data to estimate change.

To achieve this objective, this work poses four research questions:

P1. How do non-formal learning settings impact students' understanding of optical principles compared to traditional classroom instruction?

P2. What specific cognitive and learning outcomes are influenced when news-based resources are integrated into non-formal STEM learning settings to teach optical principles

P3. What are the key pedagogical features in non-formal settings that contribute to deep learning in optics?

P4. How do contextual differences (rural vs. urban, and Latin America vs. other regions) moderate learning outcomes and design features in non-formal optics education?

To obtain an optimal and ethical search, which is traceable and whose validity can be guaranteed, it has been carried out considering the criteria of the PRISMA declaration [16, 17]. The documents analyzed correspond to the search in the databases: Scopus, Web of Science (WoS), ERIC and Elicit, an AI-powered research assistant designed to facilitate literature reviews. The search strings associated with each database and the Elicit prompt used for supplementary discovery are shown in Figure 1.

A. Search strategy

We searched Scopus, Web of Science (Core Collection), and ERIC (1990 – 2025). Base strings combined optics terms (optics, reflection, refraction, image formation) with non-formal settings (non-formal/informal, museums, camps, outreach/after-school) and school-age terms (students 5–18). Optional add-ons retrieved subsets on media/interactive visualizations (PI2) and rural/Latin America (PI4). Filters included peer-reviewed articles/proceedings in English/Spanish. Additionally, Elicit was used as a supplementary discovery tool to identify records potentially missed by the primary databases. Full Boolean strings appear below; PRISAM counts are reported in the next subsection.

Scopus: (optics OR optical) AND (education OR learning OR teaching) AND (non-formal OR informal OR out-of-school OR extracurricular)

Web of Science (Core): (optics OR optical) AND (education OR learning OR teaching) AND (non formal OR informal OR out-of-school OR extracurricular)

ERIC: (optics OR optical) AND (education OR learning OR teaching) AND (non-formal OR informal OR out-of-school OR extracurricular)

B. Eligibility

Records were eligible if they: (i) involved learners aged 5–18; (ii) targeted optics content; (iii) took place in a non-formal setting (eg., museums, university labs, after-school/outreach, camps); (iv) included a comparator, either formal instruction or a pre–post baseline within the same group; and (v) reported validated outcomes for conceptual understanding (secondary outcomes: transfer, motivation, self-efficacy).

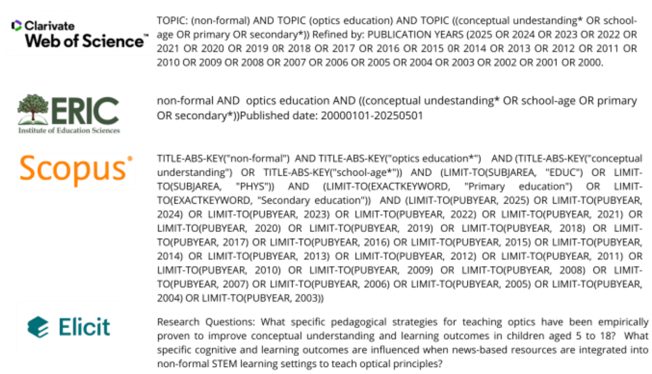

FIGURE 1. Search expressions used in the consulted databases.

C. Study selection and PRISMA flow

Following PRISMA, 723 records were identified across sources. After de-duplication, 321 unique records were screened at title level, excluding 170. 151 abstracts were assessed; 70 full texts were retrieved and evaluated. 32 full texts were excluded with reasons, yielding 38 studies included in the qualitative synthesis (no meta-analysis). PRISMA counts are shown in Table II and Figure 2.

TABLE II. PRISMA counts.

Step	Symbol	Count	Notes
Records identified Web of Science (Core)	N_1	95	1990–2025; EN/ES; Article/Proceedings; SCI-EXP/SSCI/ESCI
Records identified Scopus	N_2	40	1990–2025; EN/ES; Article/Conference Paper
Records identified ERIC	N_3	443	Peer reviewed; Elementary/Secondary; 1990–2025; EN/ES
Other sources (Elicit, snowballing)	N_4	145	Only peer-reviewed; and eligible records
After de-duplication	N_5	321	Duplicates removed $= 723 - 321 = 402$
Title screening excluded	N_6_excl	170	Screened at title level from N_5
Abstracts assessed	N_7_abs	151	-
Full texts assessed	N_7_full	70	-
Full texts not retrieved	N_7nr	0	0
Full text excluded (with reasons)	N_8_excl	32	See Figure 2 for reason codes.
Included in qualitative synthesis	N_incl	38	No quantitative meta-analysis was conducted

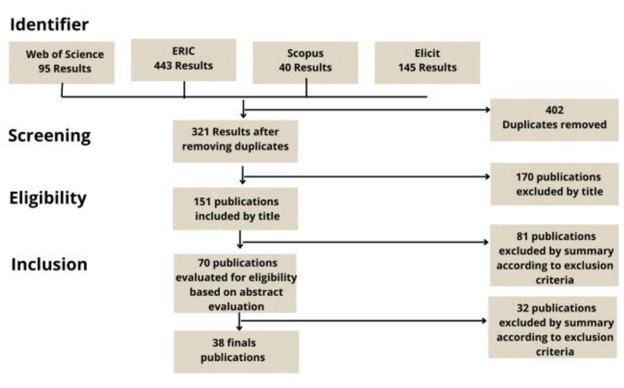

FIGURE 2. Diagram of the publication selection procedure, based on the PRISMA Declaration model (Moher et al., 2009).

Study selection summary. Inclusion/exclusion criteria (Table 1) were applied at each stage of screening. PRISMA counts are summarized in Table II and visualized in Figure 2. The review then proceeded to data extraction (design, context, intervention, measures, outcomes) to support the impact synthesis. A comparative overview of the included studies appears in Table III, with the subset addressing PI2 detailed in Table IV.

TABLE III. Comparative Overview of 26 Studies on Non-Formal Optics Education: Contexts, Strategies, and Outcomes.

Paper	Study Setting Type	Sample Size	Grade Level	Learning Environment Description
Hohrath et al., 2024 [1]	Out-of-school university lab	142	7th/8th grade	Real laboratory at a university; students investigated sun thalers using various light sources and apertures in guided or self-determined groups
Rathi et al., 2024 [18]	School-based outreach (22 schools)	1200	10th grade	Practical demonstrations and hands-on workshops using a Ray Optics Kit in classrooms
Raju et al., 2014 [19]	School-based workshop	NR	Upper primary	Workshops in upper primary schools near college; group activities on optics concepts
Semenova, 2005 [20]	Extra-curricular course	NR	Primary	Additional course for primary children; simple experiments and demonstrations
Isma and Nurlaela, 2024 [21]	Formal classroom (quasi-experimental)†	48	11th grade	Cognitive apprenticeship model in regular classes; focus on optical instruments
Udupa and Goddard, 2022 [22]	Summer camps and schools (mixed)	NR	9th grade	Table-top experiment introducing optical imaging principles using off-the-shelf parts
Efendi and Prima, 2020 [23]	Formal classroom† (private secondary schools)	26	8th grade	Project-based learning; students made homemade projectors
Johnson et al., 2007 [24]	Informal science education program	NR	Middle School	Hands-On Optics (HOO) program; national outreach to underrepresented students
Masi, 1995 [25]	Out-of-school lab/summer program	NR	Junior High	Summer and extension classes; college students taught junior high students' optics via hands-on experiments
Catena, 2024 [26]	High school formal classroom†	60	Secondary school	The students participated in a Teaching Intervention Module (TIM)

				on optical spectroscopy,
Kurniawati, 2018 [27]	Four senior high schools	128	High	Students took exams and interviews on optics concepts, particularly refraction, image formation, and laws of reflection,
Planinić, 2024 [28]	Formal educational environment†	Control grupo: 140 Experimental group:138	Secondary School	Lecture-based in control group, whereas in the experimental group, an inquiry-based teaching sequence was used, involving guided experiments and exploration activities related to wave optics.
Costa, 1997 [29]	classrooms during regular class time and in after-school voluntary sessions, in rural and urban environments	400	preschool or elementary levels	The emphasis was on active, hands-on experimentation, encouraging students to observe, discuss, analyze critically, and explore physics concepts
Leonard, 2012 [30]	Formal classrooms†, rural and urban environments	166	Middle school students	teachers adapted the curriculum to meet educational standards, and students actively engaged in hands-on activities related to optics and astronomy
Gero, 2014 [31]	Formal Classroom† (private high school)	14	Junior High School	It includes theoretical lessons, laboratories, project work, and a final team project where students design and implement an electro-optical system
Leonard, 2013 [32]	Formal classroom†	186	7th/8th grade	Students engaged in hands-on and theoretical activities
Juárez, 2015 [33]	Formal classrooom†	NR	Secondary school	Specific didactic proposal to teach optical phenomena, experimental activities
Sparks, 2010 [34]	Formal educational environment†	NR	High school	The classroom involved weekly written feedback from students on the activities, fostering an interactive and inclusive learning atmosphere.
Galili, 2000 [35]	Formal classroom†	NR	High school	Physics classes wherein students' prior knowledge was assessed through written responses and drawings.
Ndihokubwayo, 2020 [36]	Formal classroom† Urban	153	Secondary school	Physics laboratories, digital resources such as PhET simulations and YouTube videos.
Dokter, 2010 [37]	Formal Classroom†	NR	Primary And Secondary school	Classrooms and laboratories where diagnostic questions and probes are used to assess students' prior knowledge and understanding of optical concepts in real-time.
Anamezie, 2024 [38]	Formal Classroom† Urban	160	Secondary school	The classes were typical secondary school settings, with regular teachers, supervised by the researcher, emphasizing a formal classroom environment.
Chu, 2014 [39]	Formal Classroom† Urban and rural	1149	Secondary school	Classroom settings where students responded to diagnostic test items related to optics concepts, particularly light propagation and object visibility.
Uwamahoro, 2021 [40]	Formal Classroom† Urban	153	Secondary (public)	The learning environment is comprised of traditional classrooms with and without physics laboratories. instruction through conventional methods, while others used digital resources such as PhET simulations,
Tekos, 2009 [41]	Formal Education† (rural and urban)	140	Primary	designed based on constructivist principles, student-centered, collaborative, problem-solving, and task-based with teacher scaffolding.

Afriani, 2019 [42]	Formal Classroom† (public)	20	Junior high school	Incorporated guided inquiry laboratory activities with embedded videos, encouraging active participation, group work, and autonomous learning using multimedia resources and technology

Note. This table reports a subset of the 38 studies included in the qualitative synthesis (see Table 2 and Figure 2). Studies are retained here only when they provide sufficient detail on context, strategies, and outcomes to enable cross-study comparison. Entries conducted strictly in formal-classroom settings are flagged with † and are included only when directly connected to school-based outreach or museum-integrated activities relevant to non-formal learning aims. The complete set of included studies appears in the master list (Appendix/Table S1). Abbreviations: NR = not reported; † = formal-classroom study.

Regarding Research Question 2, Table III summarizes the principal results on the integration of news articles and interactive visualizations in non-formal optics education.

Table IV provides a comparative overview of eleven research articles that investigated the impact of non-formal STEM learning interventions on students' understanding of optical principles. The studies vary in design-ranging from experimental and quasi-experimental to qualitative and exploratory approaches. Learning contexts span diverse environments, including university laboratories, after-school programs, science centers, school classrooms, and museum-integrated programs. Assessment methods include both objective tools (e.g., eye tracking, pre/post-tests) and subjective measures (e.g., surveys, interviews). Across the studies, key learning outcomes reported include enhanced knowledge transfer, scientific curiosity, motivation, critical thinking, problem-solving abilities, and inquiry skills. This table highlights both the methodological diversity and the range of educational settings and outcomes explored in the research corpus.

TABLE IV. Summary of key characteristics of the included studies analyzing the impact of non-formal STEM interventions on students' optical learning.

Paper	Study Design	Learning Context	Assessment Method	Primary Outcomes
Greussing et al., 2020 [43]	Intervention study (experimental, multimethod)	University eye tracking lab (news-based science visualizations)	Eye tracking, cued retrospective reporting, memory test, online/posttest surveys	Knowledge transfer, scientific curiosity, motivation
Johnson et al., 2007 [33]	Intervention study (program description)	After-school programs, science centers, camps, workshops, clubs, classroom	No mention found	Critical thinking, problem solving, inquiry skills
Parno et al., 2019 [44]	Intervention study (quasi experimental, pre/post)	School classroom (grade X, Indonesia)	Pre/posttests (Optical Instrument Problem Solving Skills Test)	Problem Solving abilities
Porto & Zimmerman, 2010 [45]	Qualitative study; case study	Museum exhibit in school (The Museum Goes to School program)	Video recording, observational notes, interviews	Scientific curiosity, motivation
Gorghiu & Santi, 2016 [46]	Exploratory, descriptive study	National program, non-formal science activity	Student feedback questionnaire (post intervention)	Motivation, knowledge transfer, creativity, self-confidence, critical thinking, problem solving, inquiry skills
Martínez, 2022 [47]	Intervention study (quasi experimental, pre/post)	University of Extremadura in Badajoz, Spain (physic lab)	Pre- and post-intervention to evaluate changes in cognitive variables and teaching self-efficacy.	The results revealed statistically significant improvements in both variables-knowledge and teaching self-efficacy-for the group that used STEM tools and hyper-realistic simulations.
Bondani, 2014 [48]		School classroom environment, integrated into existing curricula or as supplementary activities, open days, exhibitions	Use of the "LuNa" teaching methodology based on portable experimental modules for teaching optics	Enhanced student understanding of physical phenomena through hands-on experimentation
Moreno, 2001 [49]	Intervention study socio-historical and cognitive approach	Classroom and laboratory	Evaluation methods include assessments of knowledge and skills through practical activities	Increased motivation through advanced technologies, and strengthening habits and skills related to

			(labs, projects, workshops)	engineering.
Magnani, 2014 [50]	Intervention study (combines artistic activities with teaching concepts of optics)	Elementary School classroom	Artwork and projects like spectroscopes and kaleidoscopes	Enhanced student engagement and interest in learning about light and color
Kim, 2015 [51]	Design-based research	Classroom informal environment focused on science	Qualitative assessment, analysis of multiple data: activity recordings, modeling artifacts, pre- and post-event surveys,	Skill development, improved conceptual understanding
Xu, 2021 [52]	Design-based research, (iterative cycles of design, implementation, evaluation and redesign of pedagogical interventions)	Classroom Primary School	Pre/post tests, design of a periscope	Modest progress in understanding concepts about light,

Focusing on the use of information resources such as interactive visual news in non-formal STEM education settings reinforces previous findings on the effectiveness of non-school interventions in optics learning. Among the studies analyzed, the study by Greussing et al. (2020) stands out as the only one that directly evaluated the effects of animated visualizations based on scientific news. This study demonstrated significant improvements in knowledge transfer, scientific curiosity, and student motivation, as evidenced by memory tests, eye-tracking, and post-intervention surveys [43].

Other studies within the same analysis, although not directly using news-based resources, confirmed that hands-on activities, museum exhibits, and project-based approaches also enhance skills such as critical thinking, problem-solving, creativity, and self-confidence. These findings underscore that contextual authenticity, sustained engagement, and pedagogical flexibility are key elements for achieving meaningful learning in complex topics such as optics.

However, direct evidence on the use of news resources in informal settings remains limited. This highlights an important gap and an opportunity for future research seeking to integrate relevant and accessible media materials into situated pedagogical approaches, especially in rural contexts.

IV. RESULTS

We synthesized 38 studies spanning museums, university labs, after-school/outreach initiatives, summer camps, and school-based/museum-integrated activities. Given the heterogeneity of outcome measures and instruments, we did not conduct a meta-analysis; instead, we present a direction-of-effect synthesis organized by the four research questions (PI1–PI4), with a comparative subset summarized in Table III.

PI1. Conceptual understanding.
Most studies report positive pre–post or comparative gains in conceptual understanding (reflection, refraction, image formation). When reported, effects are larger in programs combining guided inquiry with sustained hands-on work ([e.g., multi-session camps/clubs]) than in single-visit formats. Short, single-session outreach typically shows modest but significant gains.

PI2. News-based and interactive visual resources.
In smaller subset studies, integrating science-news pieces and interactive/animated visualizations is associated with improved knowledge transfer and motivational outcomes (curiosity, self-efficacy). Effects are clearest when visuals are (i) directly mapped to target misconceptions and (ii) embedded in inquiry prompts rather than shown passively.

PI3. Pedagogical features are associated with larger gains.
Across studies, four features recur in higher-gain interventions: (1) perceived authenticity (real-world tasks, community relevance), (2) guided inquiry (explicit scaffolds for prediction–observation–explanation), (3) sustained hands-on intensity (manipulation over multiple sessions), and (4) low-cost materials and simulations (complementary use of tangible artifacts and PhET-like tools). Duration and teacher facilitation quality emerge as consistent moderators.

PI4. Rural vs. urban, Latin America vs. other regions.
Evidence from rural contexts is scarce (<10% of included studies), revealing an equity gap. Available studies suggest that low-cost materials, culturally relevant examples like contextual artifacts, and community-based venues mitigate resource constraints and sustain engagement; however, sample sizes are small and follow-ups rare. Comparative evidence between Latin America and other regions remains limited, warranting cautious interpretation.

Study characteristics
Across the 38 included studies, most were conducted at the lower secondary level (ages 12–15; 17/38, 44.7%) and the upper secondary/high-school level (16–18; 14/38, 36.8%). Primary education accounted for 6/38 (15.8%), and preschool for 1/38 (2.6%). Percentages sum to ~100% due to rounding.
Extraction categories (optics concepts, outcomes/instruments, comparators, pedagogical features) were informed by prior syntheses, including [53].

A. Pedagogical Strategies and Their Impact on Optical Comprehension in Non-Formal Settings

Regarding the pedagogical strategies reported in the analyzed publications, the following stand out:

Diversification of teaching methods: The incorporation of methodologies that include inquiry, experimentation, and discussion promotes a more effective understanding of optical phenomena, in addition to encouraging reflection and meaningful learning [21, 22, 25, 28, 29, 30, 32, 33, 34, 41, 42]

Active Learning through interactive laboratories and demonstrations: The use of real-time laboratories (RTP) and in-class demonstrations (ILD), where students actively participate in predictions, observations, and data analysis, helps build concepts from practical experiences. These activities encourage collaborative participation and the use of accessible technological resources, even in developing countries. Examples of these activities include students conducting experiments on polarization, birefringence, optical information transmission, diffraction, fluorescence, and scattering. For example, building and manipulating simple telescopes to understand image focusing, or simulating atmospheric distortions using mineral oil to understand adaptive optics [24, 36, 34].

The "Experiment-Guide-Theory" approach: Students conduct basic experiments, receive theoretical explanations, and participate in discussions and innovative experiments. This model promotes active learning, integrates science and practice, and stimulates creativity and critical thinking. Here, teachers design activities in which students first conduct basic experiments, such as studying image formation with lenses or experimenting with different lens configurations to observe the effects produced on image focusing and magnification. Teachers then explain theoretical concepts, and discussion is encouraged to broaden understanding and promote creativity and innovation.[37].

Problem-solving and digital simulation-based teaching: Complementing the curriculum with open resources such as simulations and videos helps overcome difficulties in interpreting optical images and understanding phenomena related to different light sources. At this point, the use of multimedia resources to illustrate complex phenomena that are often difficult to visualize, such as spectral dispersion or interference, facilitates understanding and motivation. On the other hand, the integration of interactive online simulations and videos, such as those from PhET-type platforms, to explore optical phenomena and improve the interpretation of images formed by lenses and mirrors. These resources allow students to experiment virtually and reinforce concepts in contexts where complete physical laboratories are not available [47, 36, 40].

Implementing practical activities and simple experiments: Conducting experiments with low-cost materials, such as adaptive optics, and using visual and kinesthetic models promote a concrete understanding of complex concepts without requiring advanced mathematical knowledge [20, 41, 42].

Active teacher participation and encouragement of dialogue: The teacher's involvement in the different phases of the teaching process, promoting discussion and reflection before, during and after activities, is key to consolidating learning and developing scientific skills [1, 18, 19, 27, 31, 35, 38].

B. Challenges and Opportunities for Optics Education in Rural Contexts Based on Empirical Evidence

In reference to the rural context, it is necessary to carry out more in-depth studies on the effectiveness of active methodologies, since because of this review, less than 10% of the studies analyzed were carried out in the rural context. [39, 19, 41].

Rural contexts present unique challenges for optics education, such as limited access to laboratories, technological infrastructure, and specialized teaching materials often constrain students' opportunities to engage in experimental learning. Teachers in these environments may also face difficulties related to insufficient training in modern pedagogical approaches and a lack of professional development opportunities. However, empirical evidence highlights significant opportunities as well: rural settings often encourage the use of locally available resources, foster strong community involvement, and promote innovative, context-driven teaching strategies that make optical concepts more meaningful to students' daily lives. By leveraging these strengths, optics education in rural contexts can be transformed into an inclusive and relevant learning experience, bridging the gap between formal scientific knowledge and student lived realities.

V. DISCUSSION AND FUTURE DIRECTION

Three mechanisms help explain why non-formal optics activities outperform business-as-usual: (1) they lower barriers to entry through tangible, learner-controlled manipulation of phenomena; (2) they increase perceived authenticity, strengthening relevance and persistence; and (3) they externalize invisible processes via simulations/visualizations, reducing cognitive difficulty and enabling productive reasoning about light, images, and waves. Effective programs deliberately stage authenticity, use guided inquiry rather than unguided discovery, and allocate sustained hands-on time. Low-cost materials and simple optical setups—augmented with targeted simulations—are sufficient to produce meaningful gains when aligned to clear learning targets.

A. Mechanisms

Authenticity likely increases situational interest and perceived value; guided inquiry structures cognitive conflict around optics misconceptions; and sustained hands-on practice supports model revision and transfer. Low-cost materials enable repeated manipulation, while simulations make invisible processes (ray paths, interference) observable, reducing intrinsic cognitive load.

B. Limitations

(i) Outcome heterogeneity (different concept inventories and ad-hoc rubrics) limits comparability; (ii) short-term post-tests dominate (few delayed measures); (iii) selection bias in voluntary programs; (iv) under-representation of rural/Latin American contexts; (v) incomplete reporting of facilitator training and intervention fidelity.

C. Implications for practice

- Design for at least two to three sessions with explicit prediction–observation–explanation cycles.
- Tie activities to authentic local contexts (e.g., solar cookers, solar water disinfection, or greenhouse shading) to boost relevance.
- Combine low-cost artifacts (lenses, mirrors, DIY kits) with targeted simulations to address known misconceptions.
- Embed news-based prompts and interactive visuals as catalysts for transfer, not as stand-alone show-and-tell.
- Document facilitator scaffolds and materials list to support reproducibility in low-resource settings.

D. Research agenda

- Rural implementations with adequate power and delayed retention outcomes.
- Standardized, validated optics concept inventories across non-formal contexts.
- Mechanism-focused studies isolating authenticity and hands-on intensity as moderators.
- Longer-term trajectories: persistence in STEM choices after non-formal optics participation.

In addition to the quantitative and qualitative findings that demonstrate improvements in the understanding of optical principles, this study gains further relevance by addressing a broader educational context. First, it contributes to closing the gap between theory and practice by showing that authentic and experimental experiences, hallmarks of non-formal environments, allow optics learning to transcend abstraction and become a tangible, meaningful, and situated experience. This connection to real-world contexts not only fosters conceptual development but also strengthens essential skills such as autonomy, creativity, and collaborative work.

Secondly, this review provides a systematized body of evidence in a field that has traditionally been fragmented. While numerous non-formal education projects exist, few have been analyzed with methodological rigor and from a comparative perspective. By recovering studies with clear design criteria, measurable results, and thematic specificity, this research offers a solid foundation upon which other researchers, educators, and decision-makers can build or reform existing proposals.

Furthermore, the study highlights the democratizing potential of science education beyond the classroom. The experiences analyzed reveal that non-formal environments can bring scientific knowledge closer to traditionally excluded communities, offering accessible, flexible, and culturally relevant spaces. This finding is particularly significant for Latin America, where structural inequalities persist in access to resources, infrastructure, and training in physical sciences.

However, this review also identifies gaps that require attention in future research. These include the lack of longitudinal studies that explore the long-term retention of knowledge, the absence of systematic data on participants' sociocultural contexts, and the underrepresentation of experiences conducted in rural or Indigenous Latin American communities. In response to these gaps, there is a clear need to develop new studies that design, implement, and evaluate non-formal educational initiatives from a contextualized perspective-one that considers not only learning outcomes but also processes of symbolic appropriation, community engagement, and students' perceptions of relevance.

This work not only systematizes what has already been done but also charts a roadmap for what remains to be achieved: an optical education that is lived, questioned, and transformed in every space where learning is possible.

Considering these findings and gaps, we propose the development of a non-formal optics learning activity specifically designed for children in rural communities. This initiative aims to bring scientific knowledge closer to populations that often lack access to laboratory infrastructure and specialized instruction. The activity will be implemented in informal settings such as community centers, public spaces, or during cultural and school fairs and will incorporate locally relevant materials, inquiry-based strategies, and culturally responsive pedagogy.

Beyond teaching optical principles such as reflection, refraction, and light propagation, the project seeks to foster scientific curiosity, critical thinking, and symbolic appropriation of science through storytelling, exploration, and hands-on experimentation. This intervention will also serve as a case study to document the pedagogical design, implementation, and impact of non-formal education in real-world, low-resource environments.

Ultimately, this proposed activity represents a commitment to transforming optics education into an inclusive and community-rooted experience, and to validating the voices and imaginaries of rural children as co-constructors of scientific meaning. Considering draws on STEM education principles to engage students in exploring optical phenomena through the design and testing of simple instruments, such as homemade projectors or pinhole cameras. These hands-on tasks, framed as design challenges, combine physical science content with engineering practices and mathematical reasoning, offering a comprehensive learning experience tailored to the students' sociocultural context.

Recent studies illustrate a range of strategies for integrating non-formal STEM learning resources, revealing that the learning environment plays a crucial role in shaping both the type and intensity of cognitive outcomes [45]. For example, It was found that STEM activities focused on addressing real-life problems promote deep learning in students [14]. In addition, large-scale, multi-venue programs that blended hands-on activities with professional partnerships across after-school, community, and national settings strategies that supported the development of inquiry skills and critical thinking [54, 46].

Other cases, such as the museum-school integration described in reference [45], bridged formal and non-formal learning to increase curiosity and student engagement. Similarly, Parno et al. demonstrated that project-based STEM learning in formal classrooms can adopt features typical of informal education, fostering problem-solving and conceptual understanding.[49]

These cases collectively suggest that the degree of integration, from isolated interventions to sustained, community-based engagement, directly affects the learning outcomes observed. Hands-on, sustained activities are more likely to promote curiosity, motivation, and practical skills, while short-term or controlled studies tend to yield more limited gains focused on immediate engagement.

This evidence reinforces the rationale for our proposed intervention: to design a sustained, non-formal STEM learning experience in optics, tailored to rural contexts, and rooted in culturally relevant practices and student agency.

Despite its contributions, this review faces several methodological limitations that must be acknowledged. The small number of studies meeting the inclusion criteria reflects a limited research base on non-formal optics education, particularly in rural and Latin American contexts. Additionally, the heterogeneity of methodologies, sample sizes, and learning environments across the selected studies posed challenges for direct comparison and synthesis. Most of the reviewed interventions were short-term and lacked longitudinal follow-up, making it difficult to assess long-term conceptual retention and behavioral impact. Furthermore, few studies provided detailed socio-cultural information about participants, limiting the analysis of contextual variables that may influence learning outcomes. These limitations underscore the need for more systematic, context-sensitive research in this emerging field.

Consequently, this work invites a rethinking of teacher training and curriculum design. Non-formal approaches should not merely be viewed as complementary strategies, but rather as integral components that enrich educational trajectories when systematically incorporated into academic programs, pre-service and in-service teacher training, and public policies aimed at fostering a more equitable, transformative, and context-aware science education.

V. CONCLUSIONS

A review of the literature on optics teaching in non-formal settings and using STEM approaches shows a growing consensus on the effectiveness of active methodologies, interactive visualizations, and situated experiences in promoting critical thinking, curiosity, and conceptual understanding of optical phenomena [1, 21, 19]. Recent studies highlight that students' perception of the authenticity of the learning environment is a determining factor in enhancing motivation and deep learning. It is also recognized that practical experiences-even in non-school settings-can generate significant learning, especially when articulated with models of inquiry, collaborative work, and active reflection.
However, important gaps persist: most studies are conducted in urban or formal settings, with little representation from rural areas and Latin America. Furthermore, although several studies identify alternative conceptions of light (such as associating it solely with the source or the effect), a few proposals transform these findings into concrete, contextualized, and applicable pedagogical strategies in workshops or science outreach settings. We have also observed a weak evaluation of the sustained impact of these interventions and a lack of consideration for the cultural and linguistic frameworks that mediate learning in rural communities.

It is hoped that this will pave the way for filling several of the gaps identified in the literature: generating knowledge about the teaching of optics in informal and rural settings; proposing a replicable methodology that links diagnosis with pedagogical intervention; and positioning rural children as subjects capable of constructing scientific knowledge from their everyday experiences. This opens a path to strengthening epistemic equity in science education and fostering more fair, meaningful, and contextualized educational strategies.

Based on the findings of the systematic review, we propose a STEM-based pedagogical intervention tailored to rural learners and grounded in non-formal learning environments. In this context, we consider it pertinent to design a science workshop that combines experiential learning activities with a diagnostic tool for exploring students' conceptions of light [55]. Drawing on the empirical contributions of Martínez and Suárez-Rodríguez [14], this tool enables the identification of alternative conceptions among rural students, incorporating the sociocultural context as a key pedagogical dimension. Its structure-comprising open-ended questions, culturally contextualized scenarios, and visual prompts-makes it especially suitable for use in community-based and participatory educational settings. Integrating this instrument into the proposed workshop reinforces a student-centered approach and aligns evidence-based active learning strategies.

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