Systematic Review in Physics. Case Study: Relation between General Relativity and Electromagnetism

- Revisão sistemática em física. Estudo de caso: relação entre relatividade geral e eletromagnetismo

- Revisión sistemática en física. Estudio de caso: relación entre la relatividad general y el electromagnetismo

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Abstract

A systematic review methodology is adopted for application in Physics, with pedagogical and research purposes, exemplified through the case study of the relationship between general relativity and electromagnetism. In the early 20th century, Albert Einstein began developing a unified field theory between gravitational and electromagnetic interaction, although without achieving the desired outcome. The systematic review is applied to a selection of publications meeting specific research, categorization, and mathematical description criteria, rigorously synthesizing the scientific literature. The study classifies types of unification theories, analyzes temporal patterns, and maps the geographic distribution of publications, while identifying current research lines in unification via electromagnetism. The findings highlight a prominent focus on black hole modeling, driven by increasing international collaboration in electromagnetic and gravitational integration research. The review also offers relevant information for researchers in astrophysics, cosmology, and theoretical physics. Moreover, the study emphasizes the value of systematic review as a replicable educational and didactic tool, strengthening researcher training in science and technology fields. It provides a solid foundation for teaching research competencies, promoting efficient literature review, critical analysis, identification of trends and knowledge gaps, and planning of future studies; essential for undergraduate, graduate, and expert researchers alike.

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scientific research; physics; relativity; electromagnetism; black hole

Resumo

Adota-se a metodologia de revisão sistemática para aplicação em física, com fins pedagógicos e de pesquisa, exemplificada pelo estudo de caso da relação entre a relatividade geral e o eletromagnetismo. No início do século XX, Albert Einstein iniciou o desenvolvimento de uma teoria de campo unificado entre as interações gravitacional e eletromagnética, sem alcançar o objetivo desejado. A revisão sistemática é aplicada com base em publicações que atendem a critérios específicos de pesquisa, categorização e descrição matemática, sintetizando rigorosamente a literatura científica. O estudo classifica os tipos de teorias de unificação, analisa padrões temporais e realiza um mapeamento geográfico das publicações, além de delimitar as linhas atuais de pesquisa sobre unificação via eletromagnetismo. Os resultados revelam um foco proeminente na modelagem de buracos negros, impulsionado pelo aumento da colaboração internacional em pesquisas de integração eletromagnética e gravitacional. O trabalho também oferece informações relevantes para pesquisadores nas áreas de astrofísica, cosmologia e física teórica. Ademais, destaca-se o valor da revisão sistemática como ferramenta educacional e didática replicável que fortalece a formação de pesquisadores nas áreas de ciência e tecnologia. Proporciona uma base sólida para o ensino de competências investigativas, promovendo uma revisão bibliográfica eficiente, análise crítica, identificação de tendências e lacunas no conhecimento e planejamento de estudos futuros; essencial para pesquisadores de graduação, pós-graduação e especialistas.

Palavras-chave

pesquisa científica; física; relatividade; eletromagnetismo; buraco negro

Resumen

Se adopta la herramienta metodológica de la revisión sistemática para su uso en física, con fines pedagógicos y de investigación, ejemplificando mediante el caso de estudio de la relación entre relatividad general y electromagnetismo. A principios del siglo XX, Albert Einstein inició el desarrollo de una teoría de campo unificado entre la interacción gravitacional y electromagnética sin alcanzar el objetivo deseado. La revisión sistemática se aplica con trabajos publicados que cumplen determinados requisitos de investigación, categorización y descripción matemática, sintetizando de forma rigurosa la literatura científica, se clasificaron los tipos de unificación, se analizaron patrones temporales, se hizo un mapeo geográfico de cada publicación y se delimitaron las líneas actuales de investigación en unificación vía electromagnetismo. Los resultados muestran un enfoque prominente en el modelado de agujeros negros por un aumento en la colaboración internacional para la investigación en integración electromagnética y gravitacional. Además, cuenta con información de interés para investigadores en las áreas de astrofísica, cosmología y física teórica. Se destaca la utilidad de la revisión sistemática como recurso didáctico y educativo replicable que fortalece la formación de investigadores en el ámbito de las ciencias y la tecnología, proporciona una base sólida para la enseñanza de competencias de investigación, enfatizada en optimizar y analizar críticamente la literatura científica lo que permite identificar enfoques relevantes, tendencias y vacíos en el conocimiento, planificar nuevos estudios, buscar de manera eficiente bibliografía y proyectar hacia futuros trabajos esenciales para todo investigador de grado, posgrado y expertos.

Palabras clave

investigación científica; física; relatividad; electromagnetismo; agujero negro

Introduction

In scientific research, systematic review has proven to be a powerful and effective method for synthesizing and evaluating existing knowledge across various fields (Nightingale, 2009). While this approach has been extensively utilized in health sciences (González *et al.*, 2011; Manterola *et al.*, 2013) and higher education (Bearman *et al.*, 2012), its application in Physics is still developing. We propose the use of a systematic review methodology tool in physics to explore current research on the connections between general relativity and electromagnetism; focused on understanding the connection whether through unification, coupling, or other approaches. We aim to enhance academic rigor and promote greater transparency and collaboration among researchers (Houle *et al.*, 2023; Luján & Duberney, 2019) by incorporating systematic reviews into physics research.

In disciplines such as Physics, students and new researchers often face methodological challenges when conducting research, which limits the quality and impact of their work (Luján & Duberney, 2019; Morales *et al.*, 2005). In response, it is essential to provide tools that support rigorous and structured research practices (Deleon, 2024). Systematic reviews, widely established in fields such as medicine, offer an effective methodology to reduce bias, organize scientific literature, and identify gaps in existing knowledge (Reyna *et al.*, 2021). Despite being recognized as the highest level of scientific evidence (Reyna *et al.*, 2021), its adoption in Physics remains limited compared to other areas within science, technology, and education.

This work introduces and operationalizes a rigorous systematic review methodology tool, specifically adapted for application within an underexplored domain of physics. In contrast to conventional science education which seldom offers explicit guidance on how to conduct research, this methodological tool provides a structured and accessible framework for systematic inquiry, even for non-experts. Its practical application not only renders the review process transparent (detailing each stage and the parameters involved) but also ensures that it can be replicated by other researchers. Ultimately, this contribution aims to enhance research practices in physics through a clear, reproducible, and scientifically rigorous approach.

Context

Electromagnetism, consolidated by James Clerk Maxwell in (Maxwell, 1864) and experimentally confirmed by Heinrich Hertz in (Hertz, 1893), introduced the concept of electromagnetic waves as the mode through which light propagates. This discovery led to further investigations, including the famous Michelson-Morley experiment in (Michelson & Morley, 1887), which, despite its null results, was instrumental in the development of Einstein's special relativity in (Einstein, 1905b), fundamentally altering our notions of space and time. Einstein presented in the general theory of relativity, (Einstein, 2009), which redefined gravity as a manifestation of curvature of spacetime.

Throughout the 20th century, numerous attempts were made to unify the fundamental forces of nature. From Einstein's initial unification attempts, until the development of quantum field theory, physicists sought a comprehensive theory that combines gravity with other fundamental interactions. Despite these historical efforts, the search for a unified theory remains a major challenge in modern physics. In this context, a systematic review offers a valuable tool for exhaustively and methodically examining recent work on this research topic.

This review focused on studies from to , examining predominant research areas, countries of origin, and employed coupling techniques.

Physical Foundations

Classical Electromagnetic Field

The classical approach to electromagnetic field theory involves the study of Maxwell's equations (Purcell, 2013),

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\epsilon_0},\qquad \vec{\nabla}\cdot\vec{B}=0,\qquad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t},\qquad \vec{\nabla}\times\vec{B}=\mu_0\vec{J}+\mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t},$$

where $\vec{E}$ is the electric field intensity, ρ is the charge density, ϵ_0 the electric permittivity of free space, $\vec{B}$ is the magnetic induction field, $\vec{J}$ is the current density and μ_0 the vacuum permeability. The interaction of charged particles immersed in electromagnetic field is described by the Lorentz force: $\frac{d\vec{p}}{dt}=q\left(\vec{E}+\vec{v}\times\vec{B}\right)\cdot$

The electric field intensity and the magnetic induction can be written as function of potentials:

$$\vec{B}=\vec{\nabla}\times\vec{A},\qquad \vec{E}+\frac{\partial\vec{A}}{\partial t}=\vec{\nabla}\Phi,$$

where $\vec{A}$ is the vector potential, while Φ the scalar potential. To express the Maxwell's equations in tensor form (a covariant formulation of electromagnetism), the potentials let to define a 4-vector (Eyges, 2012; Foster & Nightingale, 2010):

$$A_\mu := (\Phi/c,\vec{A}),$$

where the 4-potential A_μ contains the temporal part Φ/c on with c the light speed, and the spatial part on $\vec{A}$. This 4-potential let to define the electromagnetic field tensor $F_{\mu\nu}$ (Tejeiro, 2002):

$$F_{\mu\nu} := \partial_\mu A_\nu-\partial_\nu A_\mu=\frac{\partial A_\nu}{\partial x^\mu}-\frac{\partial A_\mu}{\partial x^\nu},$$

The Maxwell's equations can be written like:

$$\partial_\nu F^{\mu\nu}=\mu_0 J^\mu,\ and\ \partial_\sigma F_{\mu\nu}+\partial_\mu F_{\nu\sigma}+\partial_\nu F_{\sigma\mu}=0,$$

with the 4-current defined by $J^\nu := (\rho c,\vec{J})$. From the Maxwell's equations, Einstein developed the special relativity thinking about the movement of charged particles and introducing the light speed as a universal constant (Einstein, 1905b; Einstein, 1905a). Next, Einstein's theory of gravitation, the general theory of relativity, will be shown.

Nº 60 • Segundo semestre de 2026 • pp. 1-24
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TED

General Theory of Relativity

After his work of ten years with several approximations to look gravity like a deformation of the space-time, Einstein presents his field equations that fulfill the next requirements: the gravity is excluded of the group of field forces by its universal range, is a manifestation of the space-time curvature; in order to maintain the relativity principle the physical laws must be independent of the coordinates system, therefore, the mathematical representation of the field equations is tensorial with the matter and energy included in the energy-momentum tensor. Finally, the geometry of space-time is described from the Riemann tensor with the field equations written like a linear combination of the Ricci tensor, the scalar of curvature and the metric tensor (Sarmiento, 2005) in the form:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa T_{\mu\nu},$$

Here, the Ricci Tensor $R_{\mu\nu} = g^{\rho\sigma} R_{\mu\rho\nu\sigma}$ the contraction of the Riemann tensor , is the metric tensor, R is the curvature scalar i.e., the contraction of Ricci tensor $R = g^{\mu\nu} R_{\mu\nu}$ and $T_{\mu\nu}$ the energy-momentum tensor with the constant $\kappa = \frac{8\pi G}{c^4}$ (Foster & Nightingale, 2010).

To have a wide vision of the general relativity from the physical concepts and the mathematical development of theory see: (Foster & Nightingale, 2010; Thorne *et al*., 2000; Wald, 2010) (Bambi, 2018). In the following section, the systematic review is applied.

Methodology

To fulfill the purposes of this review study, the methodological tool comprises the next stages: search and selection, ordering of studies and discussion of research (Sánchez, 2011; Carlessi & Meza, 2015). The search and selection stage deals with an inductive approach that starts with a general framework, obtaining a specific set of publications related to the topic. The sorting stage is an analysis that involves studying and categorizing the selected writings. The discussion stage is based on deductive reasoning that contemplates the developments and works of each study and the necessary arguments in relation to the knowledge acquired to answer the research question.

Searching Parameters

Databases provide an advanced search tool to select parameters of interest. These repositories host a considerable number of scientific articles on the subject, with journal rankings that are used to assist the reader (Scopus, s.f.; Anid, s.f.). The advanced search tools make possible the selection of articles that have been published in journals with academic peer review, simplifying the search by choosing keywords (Gusenbauer & Haddaway, 2020; Miller *et al*., 2009).

Articles that have been published by the main journals like *Physical Review Letters*, Institute of Physics and bibliographic databases: Scopus, Science Direct, Nature, the ArXiv (only the published articles), and those reported by Google Scholar. The set of mandatory keywords was specified for all articles: “general relativity”, “electromagnetism”, “unified field” or “coupled field”, with optional words related with field coupling (Ierardi *et al*., 2017), indicate how to specify the parameters according to the databases.

Once the search parameters were established, the search was conducted, and the selected articles were stored. The initial sample of articles that passed the search filter was 331. Each article responded affirmatively to each of the following questions to pass the search filter.

- Was the study published in a journal or indexed database?
- Is the study a peer-reviewed thesis or monograph?

- Does the study address any form of coupling in accordance with cosmological observations?
- Does the study handle any concept of classical or modern field unification?
- Does the study reason about electromagnetic phenomenology and relativistic gravitational?
- Is the study an investigation conducted between and ?

Selection Criteria

The proposed selection criteria (González *et al*., 2011), in the case study were:

- Articles with theoretical foundations in classical field theory through the variational principle, geometrization, and measurement of space-time, as well as the implementation and distribution of radiation fields, were studied (Halvorson, 2014; Paleo, 2012).
- Works theoretically in accordance with observational and experimental data of cosmological physics and the classical nature of light were considered. Topics in cosmological eras, astrophysical dynamics and perturbations, expansion and inflation of the universe, nature of light, magnetic polarization, and relativistic electric current (Patton, 2012).
- Formulations that have no correspondence to electromagnetism and general relativity in the weak field limit were not considered. Furthermore, studies that did not clearly demonstrate coupling were omitted. This criterion was for exclusion; studies that meet it were discarded. (Bokulich & Bokulich, 2010)

With obtained articles the selection criteria were applied, with the total number of studies reduced to 57 papers to be analyzed. Then the articles were categorized (Manterola *et al*., 2013), by an identification of the coupling or unification way. Physical action, metric, energy-momentum tensor, lagrangian density, extra dimension, teleparallelism, and other less frequent couplings were identified: such as gauge transformations in the connection, gravity-electromagnetism, and the so-called new Lorentz transformation model. The 57 selected articles were organized by category using the following questions that were considered for the article selection. Each article responded affirmatively to each of the following questions to pass the selection filter.

- Does the study address theoretical foundations for its unification or coupling formulation?
- Is the study in accordance with experimental data and observations of the universe?
- Is the study applicable in a global framework of the cosmos and phenomenology?
- Does the study clearly express in its formulation the concept of coupling or unification?

- Is the study clearly evidencing the physics of coupling or unification within its equations?
- Can the study be reduced to the original theories of classical fields?

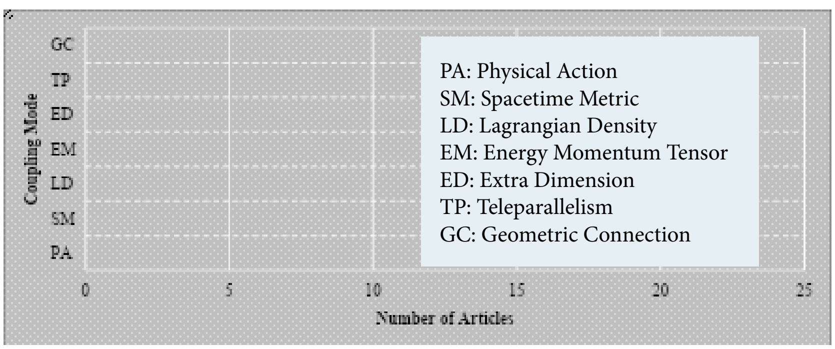
The final stage of the methodology corresponded to the discussion where the selected articles (Manterola *et al*., 2013) provided the necessary arguments in relation to the systematic knowledge of the review to answer the research question. The articles resulting from the review methodology are presented in the Annex 1 Relation modes, by citation number, title, and principal equation of coupling.

Results

The chosen articles belong to the period from 2000-2022. For the reader interested in the historical context, the articles (Dongen, 2010; FM, 2004) focus on the time window between the years 1900 and 1950. The review presents the most outstanding articles from 2000-2022 period, focusing on current research with profound ramifications in cosmology and astrophysics that represent a promising field of investigation. The sample of articles is 57, which were categorized by coupling mode as can be seen in Figure 1:

Figure 1

Coupling Mode vs. Number of Articles



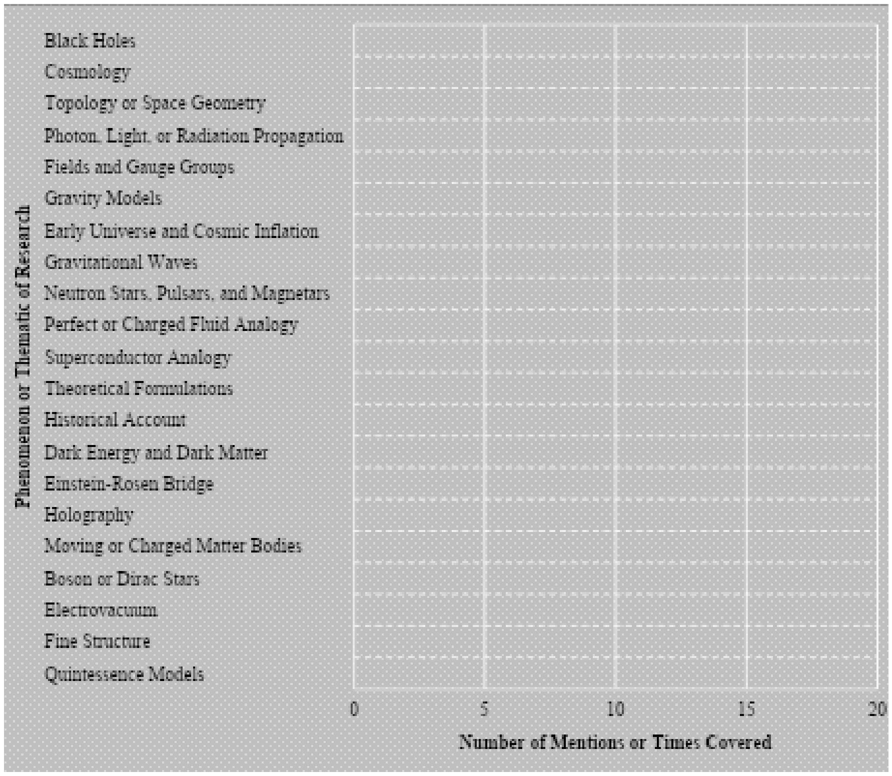
Source. Own elaboration

Regarding the total number of articles, the *physical action* category accounts for 38.6 %, representing researchers who use this distinct form of unification, in second place, the space-time metric coupling had , while Lagrangian density and energy momentum tensor had each one. The remaining is accounted by articles dealing with the other forms of coupling.

In Figure 2, the analysis goes to evaluate the physical phenomena treated in the work, the histogram of phenomena versus number of mentions in the articles is created. It should be noted that a single article could deal with more than one topic and more than one phenomenon, which makes the total amount of data is , therefore the estimated percentages are calculated over this total.

Figure 2

Topic or Phenomenon vs. Number of Mentions in Articles Histogram



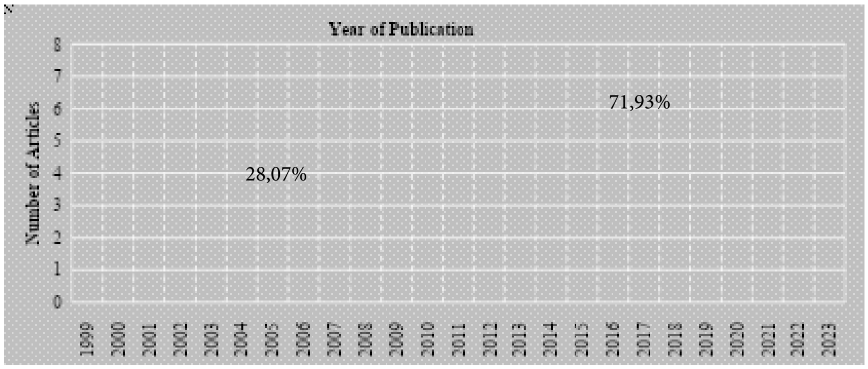
Source. Own elaboration

The study of black holes counts with 14.8 4%, in second place are works covering cosmology, the topology of space and the propagation of radiation with 9.38 % each one. Other recurring topics considered are the gauge fields and gauge groups with 7.81 %, the models of gravity with 7.03 %, the study of the early universe and cosmic inflation with 5.47 % and gravitational waves with 4.69 %. The rest like the analogy with superconductors, neutron stars, pulsars and magnetars, perfect or charged fluid, theoretical formulations, historical account, dark energy and dark matter and Einstein-Rosen bridge were presented between 2 % and 4 % of the mentions in the articles. Less frequent, phenomena such as holography, fine structure, electrovacuum, moving and/or charged bodies or matter and boson or Dirac stars appear with a frequency each of 1.56 % of the mentions, finally there are quintessence models with only 0.78 %.

It is appropriate to note the number of articles listed per publication year, the information collected can be seen in the next histogram.

Figure 3

Number of Articles per Publication Year Histogram



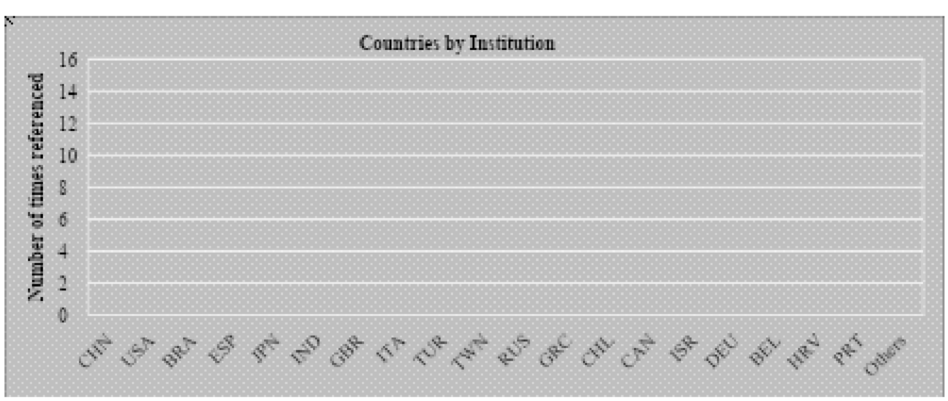
Source. Own elaboration.

Figure 3 shows the existence of a renewed interest in working on unification with the original idea of the union of electromagnetism and general relativity. Since 2012 to 2022 it is possible to observe that there is a greater number of articles per year with respect to the first twelve years, of a total of 57 articles listed, the studies between 2000 and 2011 (including 2011) correspond to 28.07 % of the total articles, and the studies between 2011 and 2022 correspond to 71.93 % of the total articles, this indicates that the research in this area has increased more than 50 % in the last 11 years.

Next, taking advantage of the filtering of studies and thanks to the review methodology implemented, information is collected about the institution's country of origin, with the purpose of locating the countries that most materialize these studies. Again, the data obtained were collected in a histogram with the countries per institution as a class mark, clarifying that a single article is elaborated by more than one author and can contribute to more than one institution.

Figure 4

Histogram of Quantity of References from Countries (ISO 3166-1 alpha3) by Institution and/or Author. Class Others: FRA, NOR, MEX, UKR, POL, ZAF, BLR, AUS, ROU, EGY; 0,99% each one



Source. Own elaboration.

Figure 4 shows that the largest contributor to research that follows or takes up the idea of unification is China with a frequency of 13.86 % of the institutions involved, followed by the United States with 12.87 % of the contributions, in third place is Brazil and Spain with 6.93 % each one, in the next three places with percentages between 3 % and 6 % are Japan, India, Great Britain, Italy, Turkey and Taiwan. The other countries represented in the articles have less than 3 % of frequency.

Discussion and Concluding Remarks

A systematic review widely used in the area of medicine, was applied and adapted to the field of physics, allowing to effectively perform this review on a large number of articles from the proper creation of search parameters, selection criteria and structure by stages of research; a task that is available to all researchers and not only exclusive to the greatest exponents of the subject under study. Thanks to the methodological tool, the resulting review highlights the current state of research, the validity of classical unification, and the various physical phenomena that can be approached from this conception promoted by Einstein at the beginning of the last century.

The total number of articles resulting from the initial search exceeded 330 articles. Due to the filtering process in the selection defined in the methodology, the number of studies to be treated was reduced to 57, a considerably lower and better number, since the final choice was focused on the studies that meet the research requirements, in addition to facilitating the management of articles when listing by categories and performing the qualitative and quantitative process of analysis.

The adoption and adaptation of the systematic review in the case study demonstrates its applicability and value within the field of physics. It avoided reading a large amount of literature not relevant to the research, did not lead to arbitrary literature searches, and categorized the information collected. This methodological approach has a great capacity to structure complex literature, reduce biases and offer high quality results.

The forms of coupling that work on unification between gravitation and electromagnetism are orienting their efforts mainly along the way of physical action, under the principle of minimum action, according to Friedman (2022), this is due to the search for physical significance in the process of classical unification, with plausible conjectures that by resorting to simplicity make it possible to fulfill the postulates of general relativity by introducing the electromagnetic interaction in a natural way.

As for the physical phenomena analyzed using coupling between general relativity and electromagnetism, it is found that research is mostly oriented on black holes 14.84 %, followed by topology and geometry of space, general

Nº 60 • Segundo semestre de 2026 • pp. 1-24
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TED

propagation of photons and cosmology 9.38 % each one, fields and gauge groups 7.81 % and gravity models 7.03 %, among more than 20 phenomena reported in the final sample. Therefore, classical unification remains a fertile field of research in theoretical physics; however, focused more on the modeling of physical phenomena where general relativity and electromagnetism are integrated than on the search for unification itself.

In the last decade (2012-2022), the interest in unified or coupled field research has increased, there is a wide variety of experimental and observational corroboration for proposed classical unified field theories; the scientific community is far from discarding the idea of a classical unified field theory. The country with the highest contribution to research with unification work is China, with 13.86 %, ahead of the United States 12.87 %, in third place is Brazil and Spain with 6.93 % each.

The present work exemplified how a systematic review properly executed produced profound analytical results, offering clear perspectives, an overview and a current view of a given research, provided a guide towards future research that can academically orient the interests of every researcher, from students in training to experts in some field under exploration, becoming a useful tool for scientific work according to their research interests. It suggests which path to take and what to work on.

This work provided valuable information for future researchers who wish to continue their undergraduate and graduate studies and who wish to contribute to the scientific community from the investigation of theoretical physics in astrophysics, cosmology, within electromagnetism and general relativity relation.

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Annex

Relation Modes

This section lists the items by coupling mode; additional information and related details can be found in the separate annexes.

Action

Table 1
Coupling Mode Action

Citation	Article Title	Principal Equation
(Ma, 2015)	Magnetically charged regular black hole in a model of nonlinear electrodynamics	$S=\frac{1}{16\pi}\int d^4x\sqrt{-g}[R-L(F,G)]$
(Kruglov, 2019)	Dyonic and magnetic black holes with nonlinear arcsin-electrodynamics.	$I=\int d^4x\sqrt{-g}\left(\frac{1}{16\pi G}R+L(F)\right)$
(Dymnikova, 2006)	Spinning superconducting electrovacuum soliton.	$S=\frac{1}{16\pi G}\int d^4x\sqrt{-g}[R-L(F)]$
(Guendelman *et al.*, 2013)	Nonsingular electrovacuum solutions with dynamically generated cosmological constant.	$S=\frac{1}{16\pi G}\int\sqrt{-g}f(R,Q)\,d^4x+\frac{1}{8\pi}\int d^4x\sqrt{-g}\varphi(X,Y)$
(Mazharimousavi *et al.*, 2011)	Thin-shell wormhole solutions in Einstein–Hoffmann–Born–Infeld theory	$S=\frac{1}{2}\int dx^d\sqrt{-g}\left[-\frac{(d-2)(d-1)}{3}\Lambda+R+\alpha L_{GB}(R_{\mu\nu\gamma\delta},R_{\mu\nu},R)+L(F)\right]$
(Bamba *et al.*, 2008)	Generic estimates for magnetic fields generated during inflation including Dirac-Born-Infeld theories.	$S=\int d^4x f_1(\phi)\sqrt{-\det(g_{\mu\nu}+f_2(\phi)\,\partial_\mu\phi\,\partial_\nu\phi+f_3(\phi)F_{\mu\nu})}+\tilde{S}(\phi,R,g_{\mu\nu})$
(Gurtug & Tahamtan, 2012)	Quantum singularities in a model of f(R) Gravity	$S=\int d^4x\sqrt{-g}\left[\frac{f(R)}{2\kappa}-\frac{1}{4\pi}F\right]$
(Chen & Jing, 2013)	Dynamical evolution of the electromagnetic perturbation with Weyl corrections.	$S=\int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}-\frac{1}{4}(F_{\mu\nu}F^{\mu\nu}-4\alpha C^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma})\right]$
(Liao *et al.*, 2014)	Absorption cross section and Hawking radiation of the electromagnetic field with Weyl corrections	$S=\int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}-\frac{1}{4}(F_{\mu\nu}F^{\mu\nu}-4\alpha C^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma})\right]$

Nº 60 • Segundo semestre de 2026 • pp. 1-24
ISSN 2665-3184 impreso • ISSN 2323-0126 Web
TED

Citation	Article Title	Principal Equation
(Liang & Harko, 2015)	Superconducting dark energy	$S_V = \int d^4x\sqrt{-g}\left\{\frac{R}{16\pi G} - \sum_{a=1}^{3}\left[\frac{1}{4}F_{\mu\nu}F^{a\,\mu\nu} + V(A^2)\right] + L_M\right\}$
(Liu *et al.*, 2016)	Non equilibrium condensation process in holographic superconductor with nonlinear electrodynamics	$S = \int d^4x\sqrt{-g}\left[R + \frac{6}{l^2} + L(F^2) - \lvert\nabla\Psi - iqA\Psi\rvert^2 - m^2\lvert\Psi\rvert^2\right]$
(Chen & Chen, 2018)	Quasi normal modes of massless scalar fields for charged black holes in the Palatini-type Gravity	$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}f(R) + \frac{1}{8\pi}\int d^4x\sqrt{-g}\phi(X,Y)$
(Herdeiro *et al.*, 2022)	Spinning gauged boson and Dirac stars: a comparative study	$S = \frac{1}{4\pi}\int d^4x\sqrt{-g}\left[\frac{R}{4G} - \frac{1}{4}F^2 + L_{(s)}\right]$
(Paul, 2022)	Viable requirements of curvature coupling helical magnetogenesis scenario	$S = \int d^4x\sqrt{-g}F(\Phi,R,G) - \int d^4x\sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right) + \int d^4x\sqrt{-g}f(R,G)[-\lambda F_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}]$
(Maity & SenGupta, 2004)	Cosmic Optical Activity in a Randall-Sundrum Braneworld with Bulk Kalb-Ramond Field.	$\mathrm{S} = \int \mathrm{d}^5\,\mathrm{x}\sqrt{-\mathrm{g}}\left[\mathrm{R} - \frac{1}{4}\mathrm{F}_{\mathrm{MN}}\mathrm{F}^{\mathrm{MN}} + \frac{1}{2}\widetilde{\mathrm{H}}_{\mathrm{MNL}}\widetilde{\mathrm{H}}^{\mathrm{MNL}}\right]$
(Harko & Cheng, 2004)	Time delay of photons of different energies in multi-dimensional cosmological models.	$S = \int d^4x\left[\frac{1}{16\pi G(t)}R^4 + \sum_{i}^{\square}\frac{1}{4g_i^2(t)}Tr\{F_{\mu\nu}^{(i)}F^{i(\mu\nu)}\}\right]$
(Bielefeld & Caldwell, 2015)	Chiral imprint of a cosmic gauge field on primordial gravitational waves	$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_P^2R + L_m - \frac{1}{4}F_{I\mu\nu}F^{I\mu\nu}\right)$
(Brihaye & Verbin, 2020)	Scalarized compact objects in a vector-tensor Horndeski Gravity	$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa}R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + H(\phi)I(g,A)\right]$
(Dale & Saez, 2012)	Cosmological perturbations in extended Electromagnetism: General gauge invariant approach.	$I = \int\left[\frac{R}{16\pi G} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \gamma\left(\nabla_\mu A^\mu\right)^2 + J^\mu A_\mu - \mu\right]\sqrt{-g}d^4x$
(Mariano & Perivolaropoulos, 2012)	Is there correlation between fine structure and dark energy cosmic dipoles?	$S = \int\left[\frac{1}{2}M_P^2R - \frac{1}{2}\left(\partial_\mu\Phi^a\right)^2 - V(\Phi) + \frac{1}{4}B(\Phi)F_{\mu\nu}^2 + L_m\right]\sqrt{-g}d^4x$
(Platis *et al.*, 2014)	Dilatonic topological defects in dimensions and their embeddings.	$S = \int d^4x\sqrt{-g}\left(\frac{c^4}{16\pi G_0}R - \frac{1}{4\alpha_0}F_{\mu\nu}F^{\mu\nu} + L_m\right)$
(Kar *et al.*, 2002)	Does a Kalb–Ramond field make spacetime optically active?	$S = \int d^4\,x\sqrt{-g}\left[\frac{1}{16\pi G}R(g,T) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\widetilde{H}_{\mu\nu\lambda}\widetilde{H}^{\mu\nu\lambda} + \frac{1}{\sqrt{G}}T^{\mu\nu\lambda}\widetilde{H}_{\mu\nu\lambda}\right]$

Source. Own elaboration.

Metric

Table 2. *Coupling Mode Metric*

Citation	Article Title	Principal Equation
(Blinder, 2001)	General Relativistic Models for the Electron.	$ds^2 = -f_{(r)}dt^2 + \frac{dr^2}{f_{(r)}} + r^2d\theta^2 + r^2sin^2\theta d\phi^2$
(Sert, 2017)	Radiation Fluid Stars in the Non-minimally Coupled	$ds^2 = -\left(1-\frac{2M}{r}+\frac{\kappa^2Q^2}{r^2}\right)dt^2 + \left(1-\frac{2M}{r}+\frac{\kappa^2Q^2}{r^2}\right)^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\phi^2)$
(de Souza & Opher, 2010)	Origin of Magnetic Fields in the Central Engine of Gamma Ray Bursts.	$ds^2 = -\left(1-\frac{2M}{r}+\frac{\kappa^2Q^2}{r^2}\right)dt^2 + \left(1-\frac{2M}{r}+\frac{\kappa^2Q^2}{r^2}\right)^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\phi^2)$
(Skákala, 2012)	Non-extremal Reissner-Nordström black hole: Do asymptotic quasi-normal modes carry information about the quantum properties of the black hole?	$ds^2 = -\left(1-\frac{2M}{r}+\frac{\kappa^2Q^2}{r^2}\right)dt^2 + \left(1-\frac{2M}{r}+\frac{\kappa^2Q^2}{r^2}\right)^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\phi^2)$
(Afonso *et al.*, 2022)	An infinite class of exact rotating black hole metrics of modified Gravity.	$ds^2 = -f_{(r)}dt^2 + \frac{dr^2}{f_{(r)}} + h_{(r)}d\Omega^2\ d\Omega^2 = d\theta^2 + r^2sin^2\theta d\phi^2$
(Flores-Alfonso *et al.*, 2021)	Black holes and gravitational waves sourced by non-linear duality rotation-invariant conformal electromagnetic matter.	*Reissner-Nordström metric with:* $f_{(r)} = 1 - \frac{2M}{r} + \frac{Q^2e^{-\gamma}}{r^2}$
(Xulu, 2006)	Energy in the Dyadosphere of a Reissner-Nordstrom Black Hole.	*Reissner-Nordström metric with:* $f_{(r)} = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - \frac{\sigma Q^4}{5r^6}$
(Li *et al.*, 2021)	Correspondence of eikonal quasinormal modes and unstable fundamental photon orbits for Kerr-Newman black hole.	$ds^2 = -dt^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + (r^2+a^2)sin^2\theta d\phi^2 + \frac{2Mr}{\Sigma}(asin^2\theta d\phi - dt)^2$

Source. Own elaboration.

Nº 60 • Segundo semestre de 2026 • pp. 1-24
ISSN 2665-3184 impreso • ISSN 2323-0126 Web
TED

Energy-momentum Tensor

Table 3. *Coupling Mode Energy-momentum Tensor*

Citation	Article Title	Principal Equation
(Füzfa, 2016)	How current loops and solenoids curve spacetime	$R_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}^{EM} \quad and \quad \nabla_\mu F^{\mu\nu} = \mu_0 J^\nu$
(Bokulić *et al.*, 2022)	Nonlinear electromagnetic fields in strictly stationary spacetimes.	$T_{ab} = -4(\partial_F L) T_{ab}^{EM} + \frac{1}{4}(g^{\alpha\beta} T_{\alpha\beta}) g_{ab}$
(Lasky & Lun, 2007)	Gravitational collapse of spherically symmetric plasmas in Einstein-Maxwell spacetimes	$T_{\mu\nu} = T_{\mu\nu}^{F} + T_{\mu\nu}^{EM}$
(Polanco *et al.*, 2008)	Static charged fluid around a massive magnetic dipole	$T_{\alpha\beta} = T_{\alpha\beta}^{EM} + \varepsilon(u_\alpha u_\beta) + (p - \varsigma \nabla_\delta u^\delta) h_{\alpha\beta} + \tau_{\alpha\beta}$
(Khlestkov & Sukhanova, 2017)	Gravitational compactification of electrodynamic objects of wormhole type	$T_\mu^\nu = T_\mu^{\nu(EM)} + \varsigma(u_\mu u^\nu) + p(u_\mu u^\nu - \delta_\mu^\nu)$
(Luo & Isenberg, 2013)	Power law inflation with Electromagnetism	$T_{\mu\nu} = T_{\mu\nu}^{EM} + \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu}\left(\frac{1}{2} g^{\rho\sigma} \partial_\rho \phi \partial_\sigma \phi + V_{(\phi)}\right)$
(Bosch *et al.*, 2016)	Nonlinear Evolution and Final Fate of Charged Anti–de Sitter Black Hole Superradiant Instability	$T_{ab} = T_{ab}^{EM} + \frac{1}{16\pi}[(D_a\psi) * (D_b\psi) + c.c.] - \frac{1}{16\pi} g_{ab} \lvert D_c\psi \rvert^2$

Source. Own elaboration.

Lagrangian Density

Table 4. *Lagrangian Density*

Citation	Article Title	Principal Equation
(Villani, 2020)	Effects of neutron stars magnetic dipole on the generation of gravitational waves.	$L \equiv L_{(U^{\mu},\Omega_{\mu\nu},A_{\mu},F_{\mu\nu},g_{\mu\nu},R_{\mu\nu\alpha\beta})} = L_{GR} + cP^{\mu}U_{\mu} + \frac{1}{2c}S^{\mu\nu}\Omega_{\mu\nu} - J^{\mu}A_{\mu} - \frac{c}{16\pi}F_{\mu\nu}F^{\mu\nu}$
(Belvedere *et al.*, 2012)	Neutron star equilibrium configurations within a fully relativistic theory with strong, weak, electromagnetic, and gravitational interactions.	$L = -\frac{R}{16\pi G} - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} + L_{\sigma} + L_{\omega} + L_{\rho} + L_{f} + L_{int}$
(Shifflett, 2008)	A modification of Einstein-Schrödinger theory that contains both General Relativity and electrodynamics	$L(\Gamma^{\lambda}_{\rho\tau}, g_{\rho\tau}, A_{\nu}) = -\frac{1}{16\pi}\sqrt{-g}\left[g^{\mu\nu}R_{\nu\mu}(\Gamma) + (n-2)\Lambda_{b}\right] + \frac{1}{4\pi}\sqrt{-g}A_{[\alpha,\rho]}g^{\alpha\mu}g^{\rho\nu}A_{[\mu,\nu]} + L_{m}$
(Bamba, 2015)	Generation of large-scale magnetic fields, non-Gaussianity, and primordial gravitational waves in inflationary cosmology	$\mathrm{L} = \frac{\mathrm{M_P^2}}{2}\mathrm{R} - \frac{1}{4}\mathrm{e}^{-\lambda\Phi/\mathrm{M_P}}\mathrm{F_{\mu\nu}F^{\mu\nu}} - \frac{1}{4}\mathrm{g_{ps}}\frac{\mathrm{Y}}{\mathrm{M}}\mathrm{F_{\mu\nu}}\tilde{\mathrm{F}}^{\mu\nu} - \frac{1}{2}\mathrm{g}^{\mu\nu}\partial_{\mu}\Phi\,\partial_{\nu}\Phi - \mathrm{U}_{(\Phi)} - \frac{1}{2}\mathrm{g}^{\mu\nu}\partial_{\mu}\mathrm{Y}\,\partial_{\nu}\mathrm{Y} - \mathrm{V}_{(\mathrm{Y})}$
(Prix, 2005)	Variational description of multifluid hydrodynamics: Coupling to gauge fields.	$\Lambda = \Lambda_{H} + \frac{1}{8\pi}\left(\lvert\vec{E}\rvert^{2} - \lvert\vec{B}\rvert^{2}\right) - \frac{1}{8\pi G}\lvert-\vec{g}\rvert^{2} + \left(\sigma A_{0} + \frac{1}{c}\vec{j}\cdot\vec{A}\right) - \rho\Phi$
(Friedman, 2022)	A unifying physically meaningful relativistic action	$L_{(x,u)} = \sqrt{\eta_{\mu\nu}u^{\mu}u\nu - \left(l_{\mu(x)}u^{\mu}\right)^{2}} + kA_{\mu(x)}u^{\mu}$
(Williams, 2020)	Long-Range Scalar Forces in Five-Dimensional General Relativity	$L = g^{1/2}\left[\frac{c^{4}\phi}{16\pi G}g^{\alpha\beta}R_{\alpha\beta} - \frac{\phi^{3}}{4\mu_{0}}g^{\alpha\mu}g^{\beta\nu}F_{\alpha\beta}F_{\mu\nu}\right]$

Source. Own elaboration.

Nº 60 • Segundo semestre de 2026 • pp. 1-24
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Extra Dimensions

Table 5

Coupling Mode Extra Dimension

Citation	Article Title	Principal Equation
(Ravndal, 2013)	Oskar Klein and the fifth dimension	$g_{AB} = \begin{bmatrix} \eta_{\alpha\beta} + \kappa^2 A_\alpha A_\beta & \kappa A_\beta \\ \kappa A_\alpha & 1 \end{bmatrix}$
(Li, 2016)	A New Unified Theory of Electromagnetic and Gravitational Interactions	$\tilde{g}_{AB} = \begin{pmatrix} kg_{\alpha\beta} + \phi^2 A_\alpha A_\beta & \phi^2 A_\alpha \\ \phi^2 A_\alpha & \phi^2 \end{pmatrix}$
(Hadley, 2017)	Electrodynamics and time orientability	$h = \begin{pmatrix} g_{\alpha\beta} + k^2 A_\alpha A_\beta & k^2 A_\alpha \\ k^2 A_\alpha & k^2 \end{pmatrix}$
(Bubuianu *et al.*, 2021)	Kaluza Klein Gravity & cosmology emerging from G. Perelman's entropy functionals and quantum geometric information flows	$g_{\mu\nu} = \begin{pmatrix} \gamma_{ij} + \phi A_i A_j & \phi A_j \\ \phi A_i & \phi \end{pmatrix}$
(Muntean, 2008)	Mechanisms of Unification in Kaluza–Klein Theory	$g_{MN} = \begin{pmatrix} g_{\mu\nu} + \phi A_\mu A_\nu & \phi A_\mu \\ \phi A_\nu & \phi \end{pmatrix}$
(Zhang *et al.*, 2020)	Constraints on Horava-Lifshitz Gravity from GRB 170817A	$g_{\mu\nu} = \begin{pmatrix} \gamma_{ij} + \phi A_i A_j & \phi A_j \\ \phi A_i & \phi \end{pmatrix}$

Source. Own elaboration.

Table 6

Coupling Mode Teleparallelism and Gauge Transformation in the connection

Citation	Article Title	Principal Equation
(Sauer, 2006)	Field equations in teleparallel spacetime: Einstein's Fernparallelismus approach towards unified field theory	$g_{\mu\nu} = h^{a}{}_{\mu} h_{a\nu}$
(Gonzalez *et al.*, 2012)	Circularly symmetric solutions in three-dimensional Teleparallel, f(T) and Maxwell-f(T) Gravity	$S = \frac{1}{2\kappa}\int \{[f(T) + T - 2\Lambda]e^{0} \wedge e^{1} \wedge e^{2}\} + \int L_{F}$
(Bamba *et al.*, 2012)	Generation of large-scale magnetic fields from inflation in teleparallelism	$S = \int d^{4}x\lvert e\rvert\left(-\frac{1}{4}f(T)F_{\mu\nu}F^{\mu\nu}\right)$
(Nashed & Bamba, 2021)	Black holes solutions in power-law Maxwell-f(T) Gravity in diverse dimensions	$L = \frac{1}{2\kappa}\int \lvert e\rvert f(T)d^{d}x + \int \lvert e\rvert L_{em}d^{d}x$
(Mukku, 2006)	Torsion, Dilaton and Gauge Couplings	$\Gamma^{\sigma}_{\mu\alpha} = \{^{\sigma}{}_{\mu\alpha}\} - \left(T^{\sigma}_{\mu\alpha} - T_{\mu}{}^{\sigma}{}_{\alpha} - T_{\alpha}{}^{\sigma}{}_{\mu}\right)$
(Giovanelli, 2016)	'... But I still can't get rid of a sense of artificiality': The Reichenbach-Einstein debate on the geometrization of the electromagnetic field.	$\Gamma^{\tau}_{\mu\nu} = \gamma^{\tau}_{\mu\nu} + \varphi^{\tau}_{\mu\nu}$
(Cabral *et al.*, 2019)	Einstein-Cartan-Dirac Gravity with symmetry breaking	$\Gamma^{\lambda}_{\mu\nu} = \tilde{\Gamma}^{\lambda}{}_{\mu\nu} + K^{\lambda}{}_{\mu\nu} + L^{\lambda}{}_{\mu\nu}$

Source. Own elaboration.

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