education sciences

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Systematic Review

Misconceptions in the Learning of Natural Sciences: A Systematic Review

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Abstract: The determination of misconceptions among students is a prerequisite to driving conceptual, procedural, and attitudinal changes. This study aimed to investigate the causes and effects that misconceptions generate in the learning of natural sciences, as well as the basic categories of misconceptions in the learning of physics held by high school students. Under the PRISMA guidelines, the research consisted of a systematic literature review in three databases: Scopus, WoS, and Dimensions. Data visualization and analysis were supported by the following tools: VOSviewer, Bibliometrix, and ATLAS.ti. It was concluded that misconceptions do not solely depend on students' behavior; teacher training and preparation also have a direct influence on this issue. The main factors include persistent use of the didactic model of transmission–reception, the influences of students' daily experiences, decontextualization of the addressed content, limited development of research skills, usage of inadequate teaching methods, texts full of formulas, and exaggerated schemas. Physics stands out as the most studied discipline, in terms of misconceptions. Several topics were identified that contained misconceptions grouped into four main subject areas: thermodynamics, waves and sound, mechanics, and radiation and light.

Keywords: misconceptions; science learning; inquiry-based science education; systematic review

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1. Introduction

Based on the teaching–study–learning process of science, both the contents of the disciplines and the didactic models used to guide their approach in the classroom are considered priorities [1]. The broad field of natural sciences includes content from astronomy, biology, physics, geology, and chemistry [2]. In the context of their didactics, at least five models are in force: transmission–reception, discovery, meaningful reception, conceptual change, and research [3].

With the diversity of content integrated into the natural sciences, students are prepared in both in the disciplinary foundations and in the daily practice of the scientific method. In terms of didactic models, recent studies link inquiry-based learning to the promotion and strengthening of meaningful learning, as well as the development of critical thinking and problem-solving in the context of learners' lives [4–6].

Despite these findings, the traditional didactic model still persists in school classrooms, a model that has proved to be incapable of fostering critical analysis and reflection [7]. It is known that this way of teaching–studying–learning can lead to the emergence of misconceptions. This happens because memorization is privileged over deep understanding, resulting in students who can only provide superficial answers that do not connect to their daily life experiences [8,9].

In order to generate a relevant and situated didactic process, it is necessary to determine the misconceptions acquired by the students. Their lack of knowledge generates an incomplete and imprecise learning environment for concepts and procedures, as well as a space for erroneous understandings in science [10,11]. For this reason, its recognition constitutes a basic premise for the (re)construction of scientific knowledge during learning, as well as for providing suggestive and destabilizing cognitive resources [12–14].

The term misconception is complex in nature, and has been conceptualized as preconceptions, alternative ideas, convictions, conceptual obstacles, misconceptions, beliefs, and alternative frameworks [15]. Moreover, the didactic literature has other names such as children's science, prior ideas, intuitive ideas, alternative conceptions, student representations, naive beliefs, implicit theories, and common sense theories [16–20]. Others have even begun to recognize these ideas as organizing models of thought [21].

Although this is not a universal characterization, contemporary scholars prioritize three terms: prior ideas, misconceptions, and alternative conceptions [17,20]. Nevertheless, it seems that in the processes of scientific dissemination, the expression *misconceptions* has become popular. Consequently, this research framework recognizes the term misconceptions in the following way: according to the theory, they are conceived as alternative conceptions that deviate from what is scientifically accepted in various contexts; therefore, they are basic premises that must be taken into account in the (re)construction of scientific knowledge [22].

Misconceptions in the natural sciences can have a variety of origins. They can come from misinterpretations of everyday experiences to incorrect information received through informal media or cultural traditions. These misconceptions take root in students' minds and represent considerable challenges as the learners resist change, even in the face of direct, structured teaching. This phenomenon not only impedes the acquisition of new knowledge, but can also affect students' attitudes towards learning science, reducing their interest and motivation.

On the other hand, with the didactic approach, not only would the importance of this research-based model be sustained, but also its treatment in the classroom would enable conceptual, procedural, and attitudinal changes in students [23,24]. Hence, teachers must reflect on their work praxis in relation to the construction of meaningful contexts from a scientific perspective that contextualize the concepts they teach [25].

The study of misconceptions in the learning of natural sciences has been approached by various authors with multidisciplinary approaches. For instance, conceptual errors in biology teaching have been investigated, highlighting the importance of understanding students' misconceptions to improve instruction [26–28]. In the field of chemistry, students' preconceived ideas have been explored, proposing strategies to correct them and promote more solid learning [29,30]. In physics, misconceptions have been analyzed, and a gender gap in conceptual understanding has been detected [31]. Likewise, some of the most common difficulties for learning astronomy in the classroom have been summarized, and strategies to overcome them have been proposed [32]. Finally, in geology, conceptual errors in the understanding of geological processes have been studied, and the importance of contextualized and inquiry-based teaching has been emphasized to overcome these barriers to learning [33]. It must be noted that in the broad field of natural sciences, systematic literature reviews of misconceptions are limited [22].

In this context, our research focuses on identifying misconceptions in the learning of natural sciences. For this reason, the following questions were raised: What are the causes and effects generated by the misconceptions that high school students hold in the learning of natural sciences? Specifically, in the learning of physics, what are the physics topics that evidence the highest number of misconceptions among high school students?

2. Materials and Methods

A systematic literature review (SRL) was used to classify, select, and analyze research papers in an orderly, accurate, and rigorous manner [33–36]. It was carried out in the Scopus, WoS (Web of Science), and Dimensions databases, because they provide an extensive amount of metadata that are essential to perform a detailed bibliometric analysis. Moreover, these databases are recognized for their comprehensiveness and reliability in various areas of science.

During the process, the guidelines of the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement [37,38] were considered, which adequately and concisely describe the process carried out in three phases.

The first phase, the sensitive search, was conducted in April 2023. This marked the beginning of the data collection process. The key terms used were "misconceptions AND science". Then, for an extended search, variants of the terms such as "alternative conceptions" AND "natural sciences" were included. This process determined an initial set of 4.174 results in Scopus, 10,005 in WoS, and 613,418 in Dimensions.

Bibliometric maps were elaborated from the extracted metadata and with the support of the VOSviewer and Bibliometrix data visualization and analysis tools. These maps allowed an effective visualization of the most cited authors, the scientific production at a country level, the relationships, and their evolution over time.

For refining the search strategy, Boolean operators were incorporated to combine relevant terms that were related to the research event and the target population. The key terms used related to misconceptions, secondary education, high school students, and branches of natural sciences. As a result, the following strategy was generated: ("misconceptions" OR "alternative conceptions") AND ("high school" OR "secondary education") AND "students" AND ("learning" OR "learn") AND ("science" OR "natural sciences" OR "biology" OR "chemistry" OR "physics" OR "astronomy" OR "geology").

No temporal or language filters were employed, in order to conduct comprehensive research about possible changes over time. This, due to bibliometrics, indicated that countries such as Indonesia, Turkey, and the United States had the highest scientific production, so this factor was independent of language. Below are the main findings that led to the determination of an appropriate search strategy.

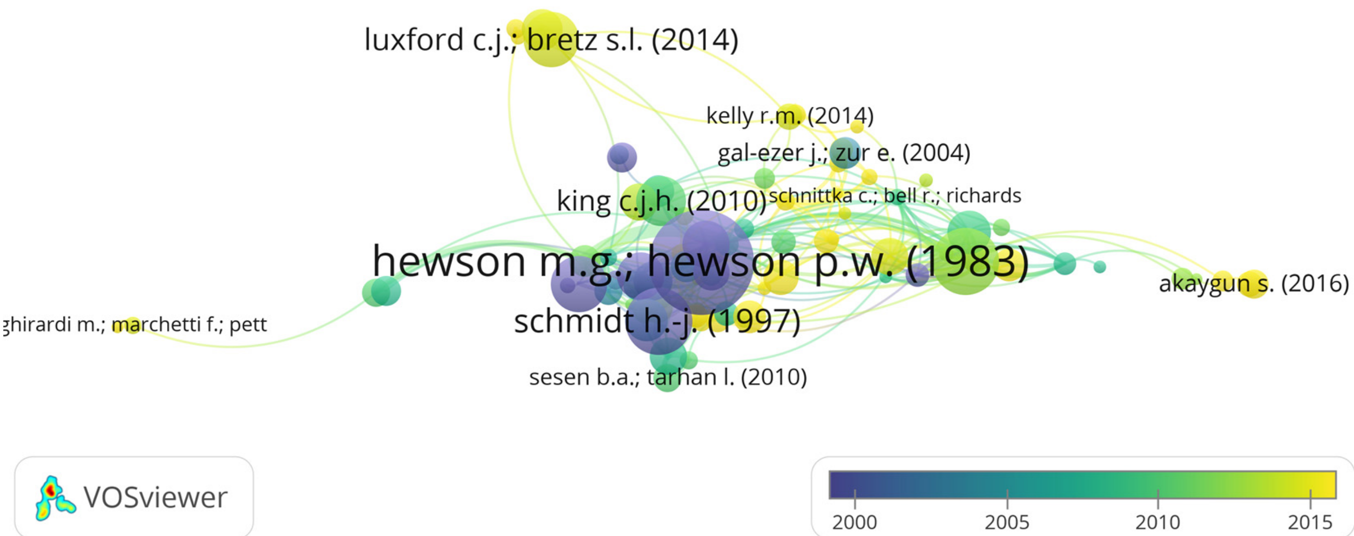
2.1. Citation of Authors

Figure 1a shows that the most cited authors are Peter W. Hewson and Mariana G. Hewson, researchers who significantly impact the study on misconceptions of natural sciences. Figure 1b shows that, in addition to being highly cited, they have a higher bibliographic pairing. In other words, they exhibit a high interconnection between studies, and frequently influence them.

The period of publication for these authors spans from 1983 to 2000. Due to this, there is wide interest in the themes these authors address, with continuous attention from the academic community; this highlights their importance and durability. This longevity suggests possible areas of future development, and establishes the need to explore new perspectives and approaches within the field.

Although the referred authors have a greater number of citations over time, currently [22], Achmad Samsudin stands out as the author with the highest scientific production, with continuous publications since 2017. On the other hand, during 2019, the most cited author was Rahma Diani. This highlights the variable dynamics within scientific production, and further demonstrates the relevance of considering both the long-term trajectory and the most recent trends.

(**a**)



(**b**)

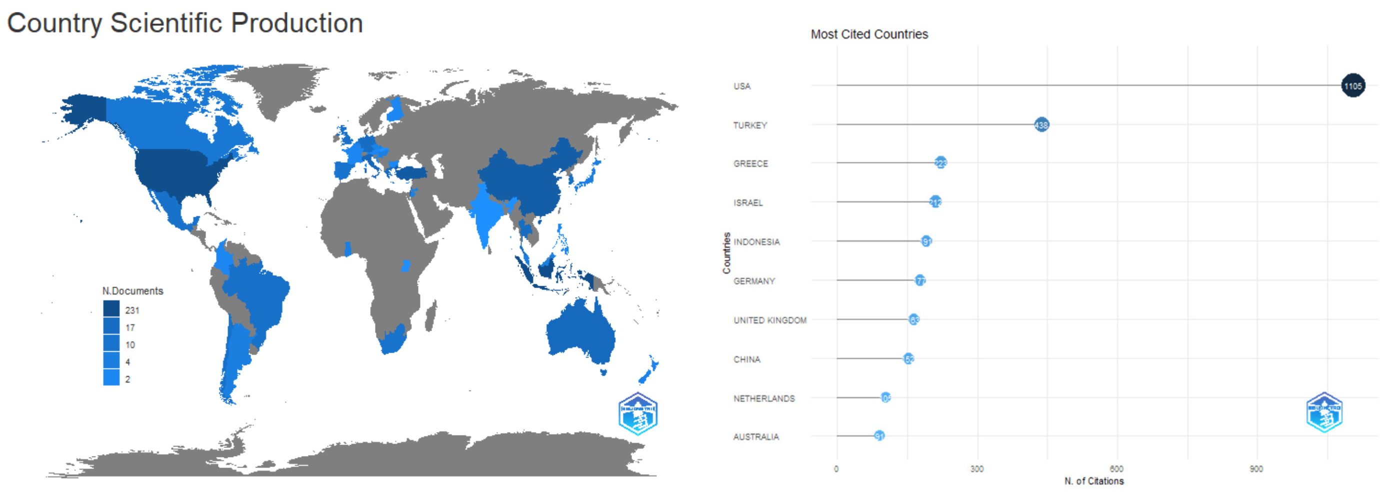
Figure 1. Citation by authors: (**a**) Heat map; (**b**) bibliographic matching.

2.2. Scientific Production by Country

The scientific production by country reveals interesting patterns in relation to the subject. As seen in Figure 2a, Indonesia stands out with 231 scientific papers. It is followed by the United States with 219, and Turkey with 72. This is evidence of the geographical diversity in research related to the research topic. The most relevant institutional affiliation is the Universitas Pendidikan Indonesia [22].

Although Indonesia has the highest scientific production in the field under study since 2020, it is not the country with the highest number of citations. As shown in Figure 2b, the United States is in the lead. This situation may be because it has a longer history of scientific contributions since 2015.

The aforementioned countries share a distinct connection. In terms of scientific production related to misconceptions in the natural sciences, Indonesia is not directly linked to the United States, but is so through Turkey [22]. In this way, the dynamics of collaborations and research networks between the countries with the highest scientific production are distinguished. The fact that Turkey has a high number of citations may be due to its role as a bridge between the two countries.



(**a**) (**b**)

Figure 2. Scientific production by country: (**a**) World Map; (**b**) citations by country.

2.3. Keywords

The keywords review provided a detailed perspective of the research trends and approaches. For the research event, 28 clusters were identified. Figure 3a shows relevant keywords "misconceptions" and "high school", "science", and "physical" and "chemistry". Also, it was deduced that there is a conceptual framework based on constructivism, since the findings highlight the importance of the active construction of knowledge by the students in direct relation to their alternative conceptions.

Regarding the time evolution of the keyword "misconceptions", Figure 3b shows relative stability in its use. In addition, a fusion occurs between the keywords "inquiry-based learning" and "secondary education". This situation reveals possible adjustments made to methodological and thematic approaches over time, which was useful when developing a search strategy.

Finally, Figure 3c reveals the tendency to provide a thematic description related to a particular science. This highlights the importance of accuracy in search, as keywords vary according to each discipline of natural sciences. Therefore, it is essential to include the terms "astronomy", "biology", "chemistry", "geology", and "physics" to ensure the relevance of the results.

Finally, the selection of articles for this systematic review was carried out through the application of inclusion and exclusion criteria linked to the information collected in the bibliometric analysis.

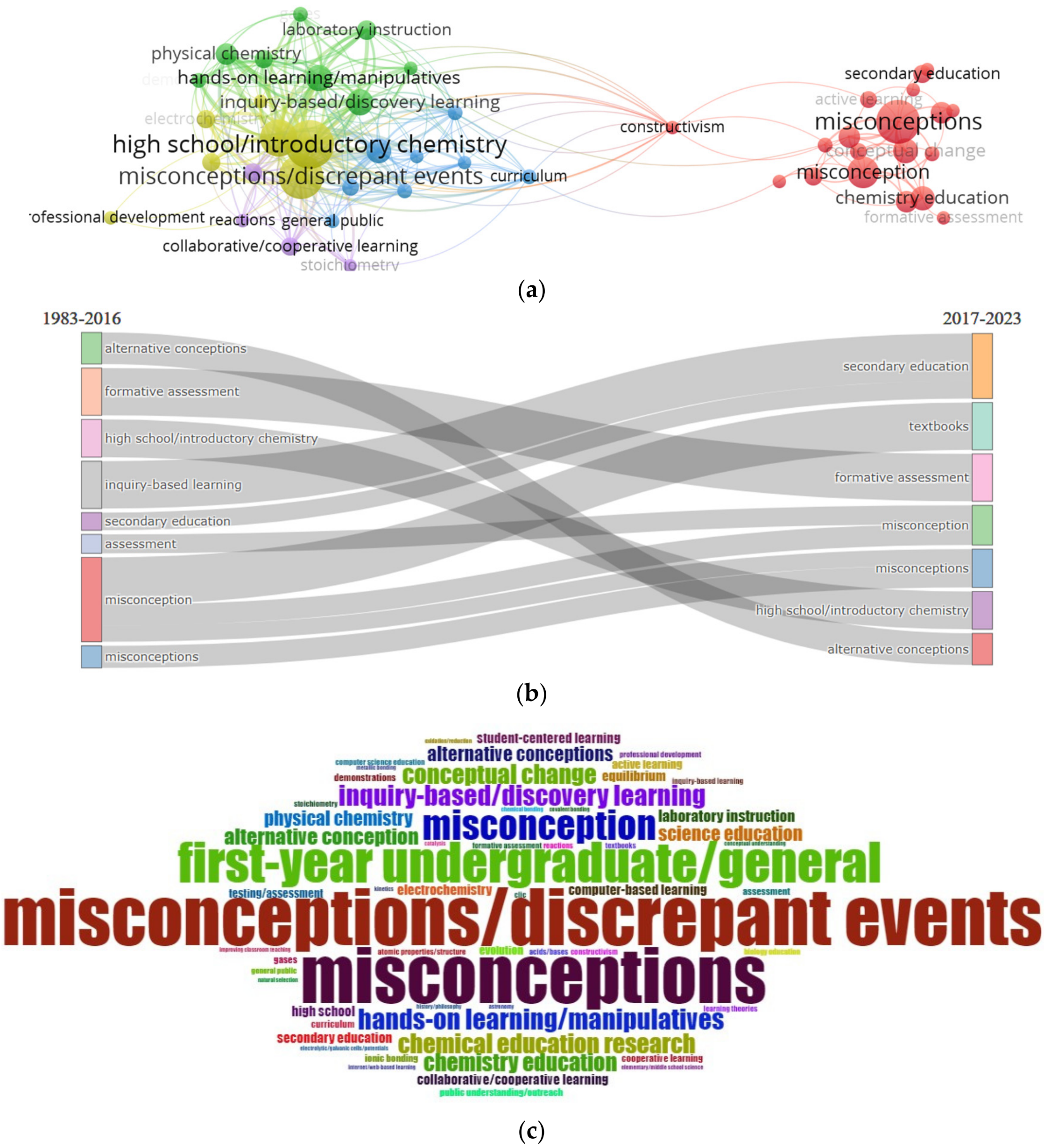


Figure 3. Keywords misconceptions: (**a**) Relationships among keywords; (**b**) evolution over time; (**c**) Word Cloud.

2.4. Inclusion Criteria

- Open access articles: Only these types of articles were included to ensure accessibility and availability of information.
- Primary research: They were selected because they provide knowledge in a more direct and reliable way.
- Target population: Articles were considered when their populations were high school students, without considering factors such as gender, race, lifestyle, and demographic location, among others.
- Research event: Misconceptions or alternative conceptions in natural sciences.
- All languages: Due to the diversity of the leading countries in publications on the subject, for example, Indonesia, Turkey, and the United States.
- Results relevant to the research event: Articles had to present specific results related to alternative conceptions or misconceptions in high school students.

2.5. Exclusion Criteria

- Reviews or meta-analyses: Articles other than primary research.
- Different from the natural sciences: Unfocused from the natural sciences.
- Populations other than secondary education: Those that do not include high school students.
- Different from alternative conceptions or misconceptions: Unidentified from the causes and effects of students' alternative or erroneous conceptions.

2.6. Review Process

Out of a total of 1036 initial articles, 378 duplicate studies were excluded in the first stage. Subsequently, after reviewing the titles and abstracts, 459 articles not aligned to the research question were discarded. After the application of the inclusion and exclusion criteria, a total of 56 studies considered eligible were obtained. From those articles, 40 were excluded because they did not provide information about students' alternative or erroneous conceptions.

Figure 4 shows the process to select 16 scientific articles that met all of the criteria established to carry out the systematic review.

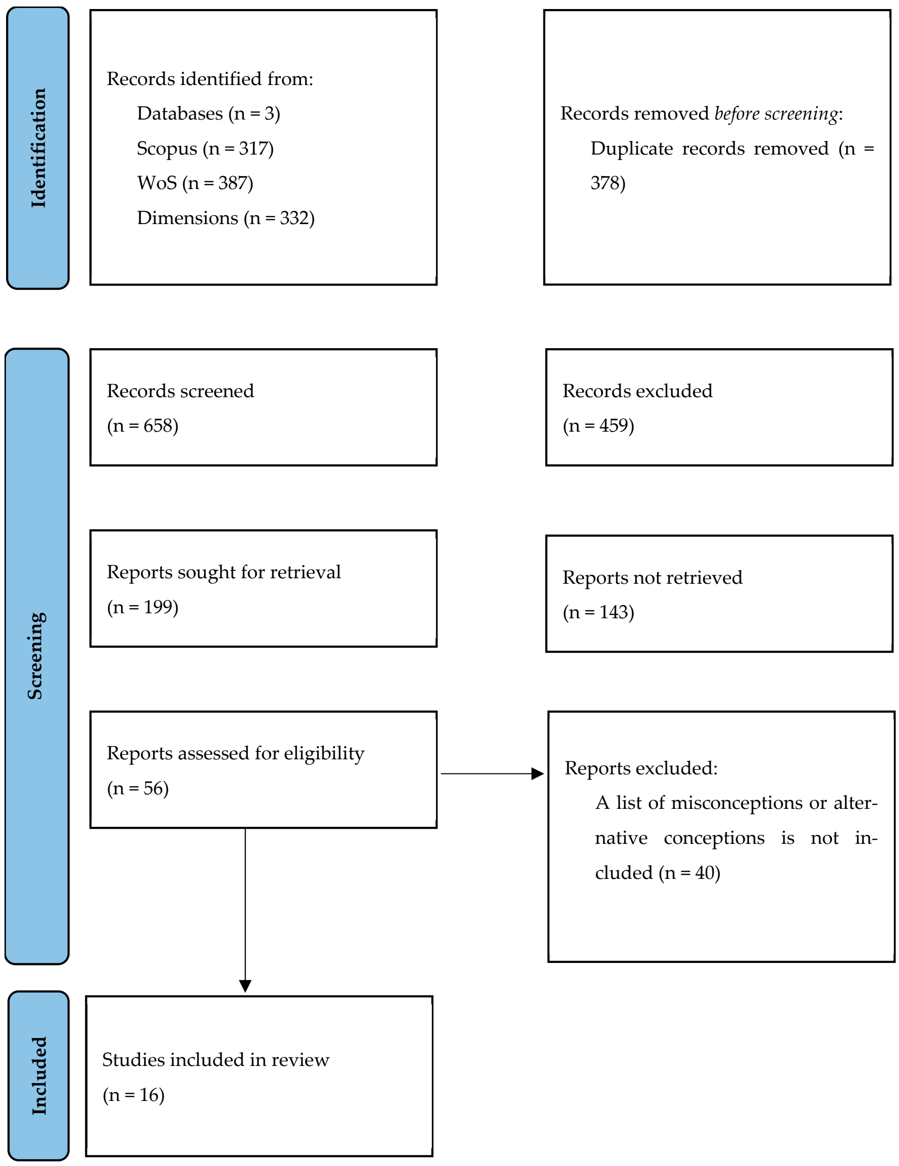


Figure 4. PRISMA flow diagram.

Subsequently, the ATLAS.ti program was used for the analysis of the data collected from the 16 essential articles. Its use provided a comprehensive vision, as well as efficient management in the handling of qualitative data. In addition, it made it possible to improve the organization, coding, and systematic analysis of information. As a prerequisite, a careful reading of the results of each study was performed to extract the most relevant information.

Thus, it was possible to identify patterns, relationships, and influences between misconceptions and the learning of natural sciences. This process ensured coherence in the information synthesis and a deep and detailed understanding of the research event.

3. Results

Lotka's law offers a valuable perspective for understanding the dynamics of academic production in a specific field [39]. According to this law, the general tendency is that most authors contribute a small number of papers on a specific topic, while a small group of researchers is responsible for most of the relevant literature in that field. Figure 5 shows that the data collected support the statement of this law.

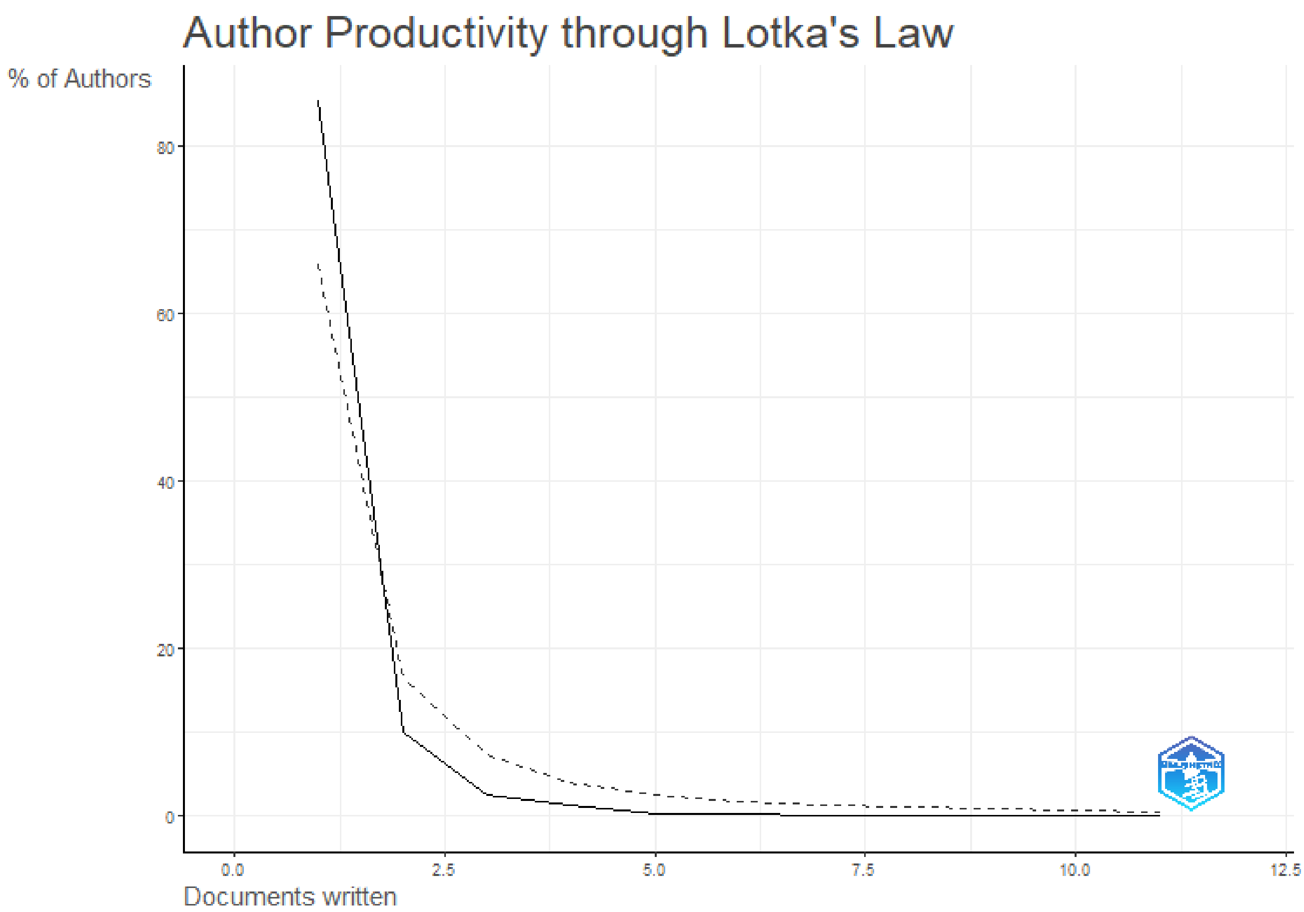


Figure 5. Lotka's Law.

Upon the fulfillment of this law, which focuses on the inequality of academic production among researchers, we highlight the importance of identifying and recognizing those authors who have excelled in the subject and who have had a significant impact in their field. This allows us to guide future research and collaborations with those authors who exert the greatest influence in their scientific fields.

As a derivation, the examination of scientific articles showed concrete results in these experimental sciences. Physics was the science with the highest volume of production and discoveries. On the contrary, no specific studies related to geology were found. In general, in the published research, the authors explore and detail factors that promote the appearance of misconceptions in the learning of natural sciences in high school students.

3.1. Causes and Effects Generated by Misconceptions in Chemistry

It is assumed that chemistry is not always easy to understand because it involves didactic processes that can be complicated for students such as prevalence use of the transmission–reception learning model; use of textbooks full of formulas that are incomprehensible to students; imitation of good examples and repetitive exercises as a priority method of study; excessive generalization of concepts, principles, and laws; decontextualization and superficiality in the way chemical problems are approached; students' personal conceptualizations that do not always agree with the scientific concepts studied; and limited support for the development of reasoning skills [40–43].

The preeminence of these factors triggers the formation of misconceptions as well as the progressive disinterest of students in their learning of natural sciences [40–43]. This is reflected in misinterpretations and a limited understanding of chemical principles.

Among the main misconceptions that remain in students' understandings, the following are mentioned:

- Air (chemical composition) [44].
- States of matter (mention of the state of matter unrelated to temperature and pressure, incomprehension of the evaporation of some liquids at any temperature, dissociation between the structure of particles in different states of matter) [44].
- Structure of matter (little knowledge or confusion about the microscopic properties of matter: number, order, spaces, size and motion of particles, configuration of molecules) [45].
- Chemical bonds (types of atoms that form them, how they are formed and what types exist, knowledge of ions) [46].
- Chemical equilibrium (equilibrium is reached when the concentration of the product is equal to that of the reactants, equilibrium is reached when the reaction rate in the formation of products and reactants is constant, the concentration of reactants and products increases during the reaction, pressure and temperature generate increases in reactants and products) [47].
- Radioactivity (unawareness of radioactive sources of natural origin, tendency to relate their origin to the use of technological devices, radiation is transmitted through the air, difficulties in interpreting the radioactive process from the atomic–nuclear perspective; possibility of changing radioactive substances with temperature or change in state, and lack of knowledge about protective measures in relation to different types of radiation) [48].

3.2. Causes and Effects Generated by Misconceptions in Biology

In biology, superficial comprehension of concepts is attributed to students' limited thoroughness [49]. Among other causes, teaching methods and teachers' explanations are cited as triggers for the emergence of misconceptions. In addition, the limited use of appropriate teaching aids or analogies might make it difficult for students to understand complex concepts.

As a cause for the permanence of misconceptions, the scientific literature also exposes the outdated and even misleading information that potentially impacts students and teachers [50]. Their origins can come from textbooks, websites, journal articles, and even curriculum guides designed by experts. Among the main categories of misconceptions are oversimplifications, overgeneralizations, use of obsolete terms, and erroneous identifications.

Among the main misconceptions that remain in students' understandings, the following are mentioned:

- DNA (confusion of terms with atom, molecule, and cell; DNA contains living cells, it is made up of amino acids that allow exchange among cells, it is found in the blood) [44].

- Cells (related to the definition, classes, but mostly to the structure and function of cellular organelles) [51].
- Human digestion (errors in relation to the mouth-to-stomach route, the order of the intestines, and the connections of the liver and pancreas to the digestive tract; incorrectly locating the place in the tube where the liver and pancreas secrete digestive juices, as well as the place where the absorption of nutrients takes place) [52].
- Classification of living beings (simplified and outdated regarding the variety of living beings into two or three kingdoms, characterization with the use of the category super-kingdom or domain is not included either) [53].
- Plants (photosynthesis only takes place during the day and at night they breathe oxygen; oversimplification of the equation represented by photosynthesis, in which glucose is placed as the main product without taking into account starch or sucrose as the most common products; overestimation of animal pollination and confusion with fertilization; and identifying algae, fungi, and corals as plants) [54].

It is imperative that both students and educators become aware of the effects that generate misconceptions, so that they can work collaboratively to minimize them in the teaching–learning of biology. On the part of teachers, the use of various teaching aids and the promotion of a more co-responsible study culture are needed.

3.3. Causes and Effects Generated by Misconceptions in Astronomy

Alternative conceptions are attributed to the use of exaggerated schemas to explain astronomical concepts. Schemas, when used appropriately, can simplify the understanding of complex concepts; however, they can lead to incorrect or incomplete understanding when oversimplifications are used [55].

Everyday experiences and superficial observations of celestial phenomena have also been found to contribute to the formation of misconceptions. The study of astronomical phenomena is difficult to understand because of their scale or distance from the observer.

Among the main misconceptions that remain in students' understandings, the following are mentioned:

- Gravity (there is no gravity in outer space or on the moon; gravity is like magnetic force; during free fall, acceleration depends on the mass of the object and the distance to the earth; confusion about the orbital motions of the planets) [56].
- Seasons (seasons occur as a result of the distance the Earth is from the sun during the year; the Earth's tilt changes direction throughout the year; the Earth's rotation affects the seasons; and the Earth's tilt changes direction throughout the year) [55,56].
- Big Bang (the Big Bang was an explosion, there was some configuration of matter before the big bang, the universe has a center, there is no evidence of the Big Bang) [56].
- Comets and constellations (comets are falling stars; constellations are stars that connect through lines and represent animal figures) [57,58].
- Solar system (the Sun revolves around the Earth, learners do not distinguish sizes among celestial bodies in the solar system nor do they represent them adequately) [58].
- Universe (place where planets are located and living beings live, stars are planets that appear at night) [58].

It has also been highlighted that both in-service and pre-service teachers have inadequate alternative conceptions in astronomy [59]. This can influence the way they approach teaching, and it directly affects students' understanding of science [60].

In the end, we suggest balancing simplification with conceptual precision. In addition, these findings highlight the importance of the continuous training of educators in didactic models for the study of science. This may support the implementation of adequate, accurate, and up-to-date teaching in astronomy.

3.4. Causes and Effects Generated by Misconceptions in Physics

Several studies [61–70] have identified some factors that contribute to the emergence of misconceptions in physics. First, these studies point to students' low comprehension of physical concepts, and their tendency to memorize formulas and concepts without really understanding them [61–70]. This results in a limited ability to analyze problems, and difficulties when establishing relationships between quantities and formulas.

In addition, students face difficulties in understanding the relationships between quantities when they are presented in graphics [61]. This leads to the construction of their own concepts, which are not always scientifically accurate and relevant [62,69]. Since they do not understand the basic concepts, they are often confused when approaching problems of greater difficulty.

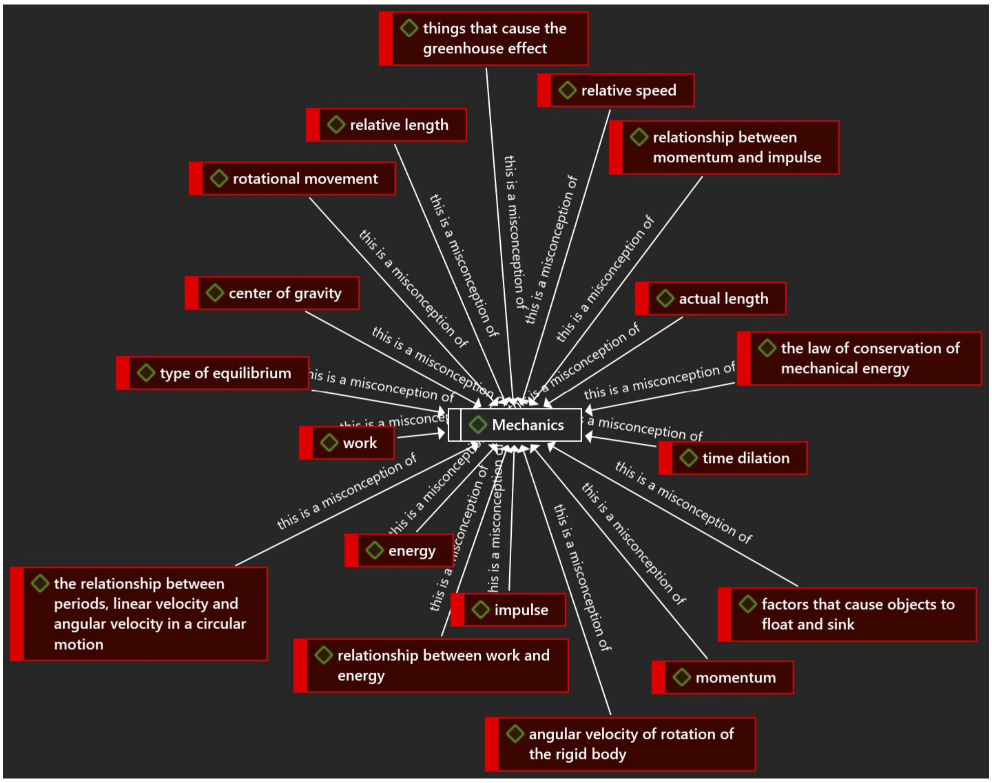
The role of textbooks is also a significant factor. The availability of books that present different versions of equations often hinders and slows down the understanding of the fundamentals of physics; teachers should spend more time explaining these variations [63,66].

Learning experiences based on memorization without comprehension, associative thinking, and incomplete or incorrect reasoning generate learning of physical concepts with shortcomings [61,64,65]. On the other hand, the immature understanding of concepts on the part of students, together with inadequate explanations by teachers and the use of inappropriate learning resources, are other causes that give rise to misconceptions in the learning of physics [63,66].

It should be noted that students' intuition is often wrong [65]. Sometimes, they have difficulty abstracting concepts properly [67,68]. Likewise, forgetting concepts or retaining them weakly, which are influenced by the opinions of their peers, also contribute to the development of misconceptions in the learning of physics [68].

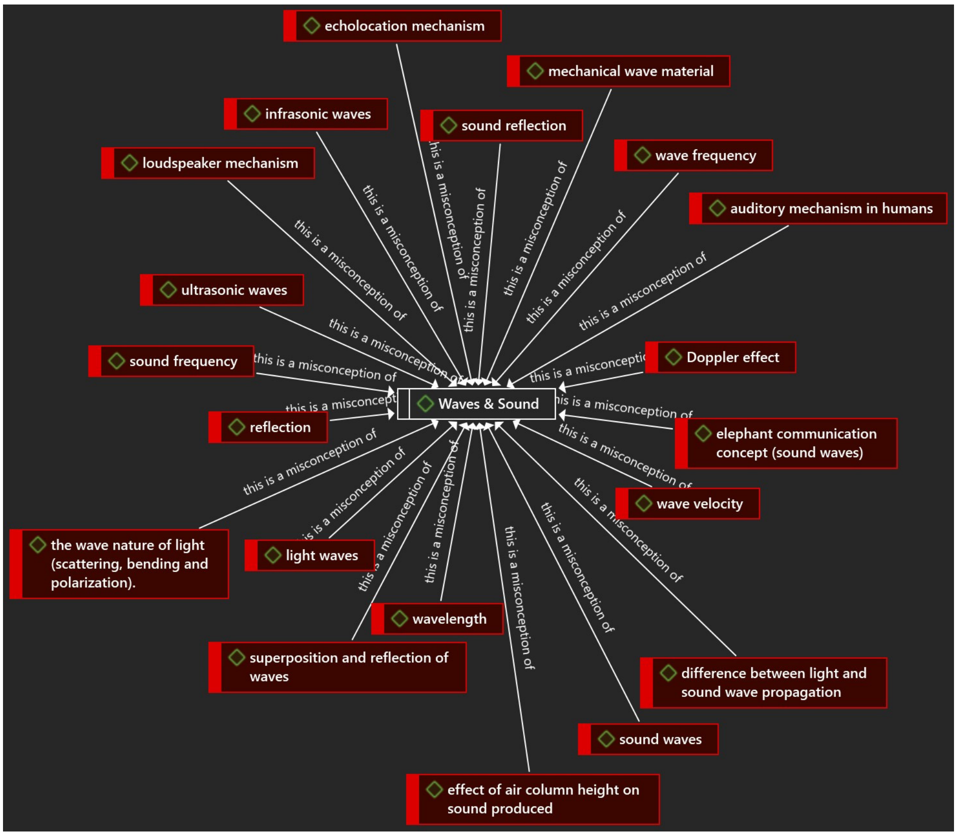
It is relevant to bear in mind that teaching–learning physics is the field with the greatest number of studies, which, as initially argued, is linked to the other natural sciences. Therefore, it is necessary to address and correct misconceptions through inquiry-based learning in all areas of science, and particularly in physics.

In response to the second research question regarding the misconceptions that arise in the learning of physics, Figure 6 shows 53.



(**a**)

Figure 6. *Cont.*



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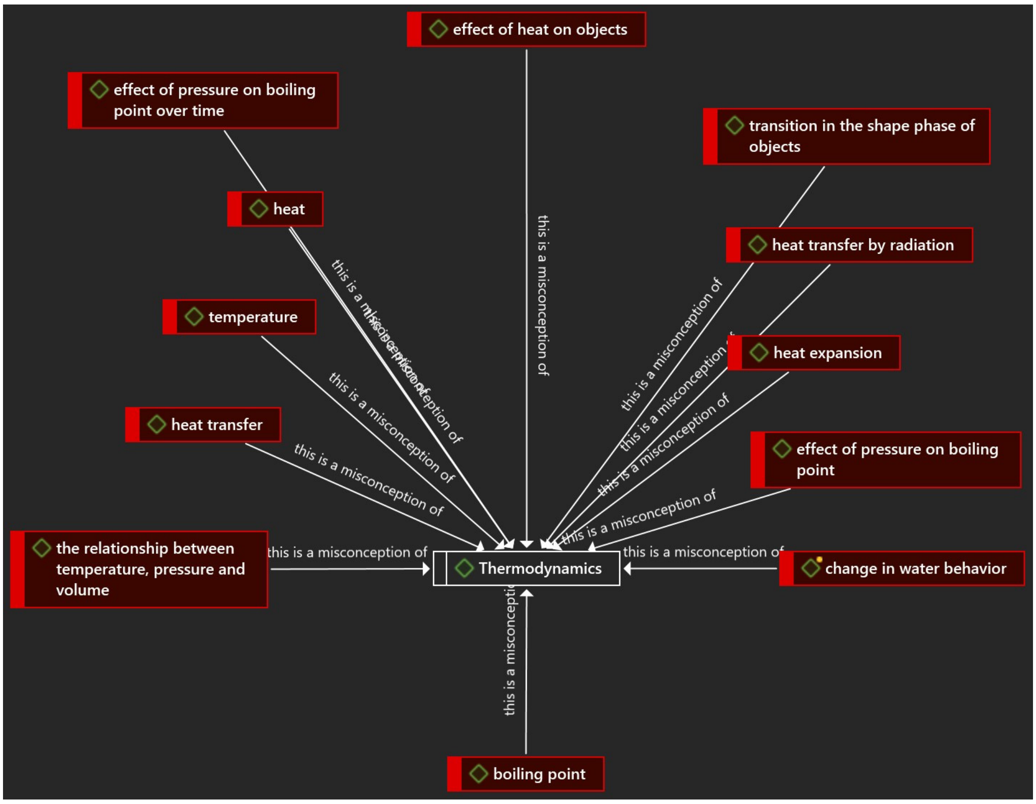

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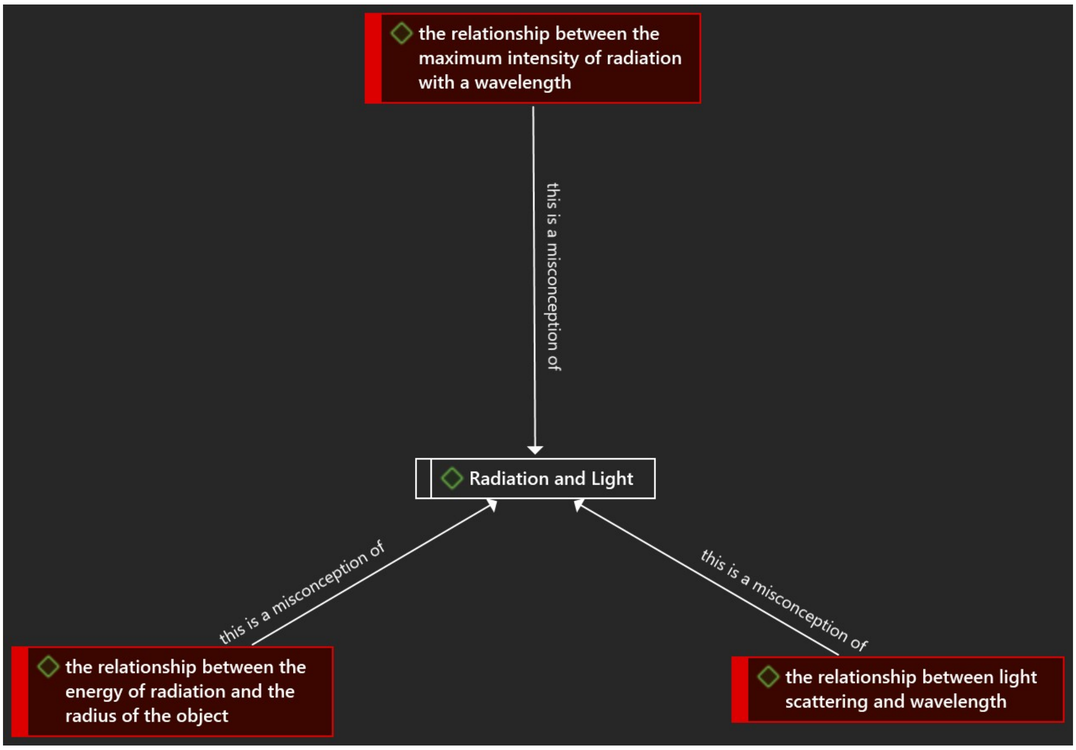
Figure 6. *Cont.*



(**d**)

Figure 6. Misconceptions in physics: (**a**) Misconceptions in Mechanics; (**b**) Misconceptions in Waves & Sound; (**c**) Misconceptions in Thermodynamics; (**d**) Misconceptions in Radiation and Light.

4. Discussion

In correlation with the findings of other researchers [4–6], the results of this systematic review suggest the relevance of adopting inquiry-based didactic models in the broad field of the natural sciences. Due to personal experiences, everyday observations and preconceptions also play a key role in the emergence of conceptual errors [61,64,65]. It is important to note that the causes do not only lie with the students, because teachers also face challenges such as using inadequate teaching aids, textbooks that do not adequately describe knowledge, and diverse teaching approaches. Therefore, it is appropriate to use interactive learning media and methods that are designed on the basis of experiences that start from the students' misconceptions and generate cognitive conflicts, which in turn cause conceptual changes [71]. All of these factors reveal the complexity of the educational environment, and the need to address these issues from a holistic point of view.

Some of the causes and effects of misconceptions present in high school students in disciplines belonging to the natural sciences (astronomy, biology, physics, and chemistry) have been pointed out. We highlight that, despite the rigor of the studies, there is limited evidence of exploration in the field of geology. This is consistent with the findings of other researchers who have indicated that education in geology is limited in several countries, and there is a lack of motivation for its study, despite the importance of raising awareness among students about underground resources, geological risks, and energy sources, among others [72].

The results obtained are consistent and common in the teaching–learning of sciences in general [43–45]. This systematic review, which addressed studies from different disciplines, also identified some effects of the persistence of conceptual errors in secondary school students. The main effects are limitations in the comprehension of concepts, prevalence of the didactic model by transmission–reception to the detriment of inquiry-based learning, scarce development of thinking skills and for problem-solving and project planning. These findings explain the lack of understanding of basic concepts as a direct cause of the occurrence of misconceptions. Other researchers also mention that the transmission–reception model, characterized by the teacher's verbal exposition and memorization of definitions and formulas, among other aspects, does not favor the development of knowledge, but rather generates erroneous conceptions [73–75].

It is significant that most of the articles reviewed and analyzed, which met the defined inclusion and exclusion criteria, belong to the field of physics. This finding suggests that the teaching–learning of physics may be more complex, and becomes a science that generates a greater proportion of misconceptions among students. This complexity is directed to the different phenomena involved in physics, which are not always intuitive, in addition to the fact that the discipline itself demands a considerable level of abstraction and appropriate logical-mathematical reasoning. Hence, we conclude by suggesting that teachers should improve their pedagogical knowledge and integrate everyday examples, in order to improve students' conceptual understanding [76].

Similarly, several topics containing misconceptions in the field of physics were identified, which can be grouped into four main categories: thermodynamics, waves and sound, mechanics, and radiation and light. Likewise, physics is intertwined with various disciplines of natural sciences such as astronomy, biology, geology, and chemistry, highlighting the importance of an integrated and coherent understanding to apply concepts in different contexts.

All of these factors have crucial implications for education, even more for the teaching–learning of the natural sciences in secondary school. Hence, educators must pay greater attention to students and their conceptions and be able to take conscious measures to address them, since the persistence of misconceptions delays the full development of a learner's ability [77]. It is also taken into account that these students' conceptions are involved in the design and implementation of science education programs, in order to guarantee meaningful learning and correct scientific literacy [78].

In the end, it was inferred that the number of citations by authors does not always reflect the level of scientific production in a given period of time. In addition, a relationship among various countries was identified that related to the study of misconceptions in the natural sciences, specifically the relationships among the United States, Indonesia, and Turkey.

As already determined [78], the findings suggest that the prevalence of conceptual errors may be global in scope, as they manifest themselves in different countries and diverse cultural contexts. This problem, which is manifested in the didactic process, is presented as an obstacle that hinders the understanding and scientific reasoning of secondary school students.

5. Limitations and Future Lines of Research

Given the nature of a systematic review, it can be noted that in this study, the results are limited to documents that met the established criteria and qualitative analysis, and did not include direct field observations.

Therefore, there is an evident need to conduct more in-depth research on misconceptions in other disciplines, with the aim of exploring and proposing new strategies and tools to diagnose and correct them.

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