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THRESHOLD CONCEPTS IN THE TEACHING OF NATURAL SCIENCES: A SYSTEMATIC REVIEW

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Abstract

A systematic review of Threshold Concepts provides a thorough and structured analysis of the existing literature related to these essential and transforming concepts in education. Threshold Concepts represent ideas or knowledge that, once understood, allow the student to access deeper levels of understanding of a discipline. These concepts are crucial, since they act as "doors" that, once "crossed", lead to a more integrated and coherent vision of a study area. In the review, various academic databases were consulted to identify relevant studies, applying rigorous inclusion and exclusion criteria. Through this process, key patterns, methodologies, and findings were detected, related to the teaching, understanding and application of these concepts. Despite the broad methodological diversity that exists in the field, as well as educational approaches and contexts, Threshold Concepts are not always addressed successfully at the curricular level or in the implementation of teaching methodologies. The limitations of this review have an impact on possible publishing bias and the diversity of research methods. However, the review stresses the need for greater integration of these concepts in education, as well as future research that explores efficient pedagogical strategies to teach them.

Keywords – Threshold concepts, systemic review, natural sciences.

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1. Introduction

Research about Threshold Concepts in the teaching of natural sciences is of great importance in the educational and scientific field. These concepts, also known as difficult concepts or key ideas, are those that are fundamental in order to understand a topic, but that students often find especially challenging. Some of the reasons that highlight the importance of researching this topic include:

1. Learning improvement: Identifying Threshold Concepts allows for educators to adapt their teaching approaches so they can negotiate epistemological transitions (Meyer & Land, 2005). By understanding what ideas are the most difficult to understand, more effective pedagogical strategies can be designed in order to promote a deeper and long-lasting learning.

2. Preventing Misunderstandings: Several mistakes and misunderstandings in scientific education stem from the lack of understanding of key concepts. When researching about these concepts, it is possible to identify the points where students usually stumble and develop approaches to address these problematic areas (Ross, Taylor, Hughes, Kofod, Whitaker, Lutze-Mann et al., 2010).

3. Promoting Critical Thinking: Understanding Threshold Concepts not only involves memorizing information, but also developing critical thinking and the ability to connect ideas. Research in this field can help to promote a deeper understanding of scientific processes and how they relate to one another (Rickets, 2010).

4. Effective Curriculum Design: Study plans can greatly benefit from identifying key concepts that need special attention. This allows a more efficient structuring of contents and helps educators to focus on the more essential aspects of natural sciences (Cousin, 2006).

Literature reviews evidence the need to delve into emerging elements of strategies, contexts or tools with which teachers approach their practices, forms of exchanging ideas and autonomous learning opportunities (Solís, Miranda, Merino & Medina, 2024) demonstrating that teacher-student relationships are fundamental for the negotiation of meaning and the transformation of their world view (Papahiu & Robledo, 2004).

An understanding of the cognitive and affective components of students offers a valuable opportunity to revolutionize the approaches and methodologies adopted in curricular, didactics, and formative design of teachers in the natural science field. From this perspective, the theory of "Threshold Concepts" emerges as a powerful lens to examine the essence of learning in specific contexts. This concepts are understood as catalysts in the cognitive journey a student makes when trying to transform their knowledge base, their identity, and their affectivity as they move forward in their learning process. Meyer and Land (2006) have identified them as tools that facilitate this change, while Cousin (2006) has described them as "curriculum jewels" due to their innate ability to deeply transform the learning experience of a student.

Given this context, it is fascinating to explore the contributions of this theoretical framework in the definition of didactic and curricular elements within the science classroom, with the purpose of shaping and transforming the world perceptions of students during the educational process.

In this scenario, an essential question arises: What are the main trends in empirical research regarding Threshold Concepts in natural sciences? The purpose of this study is to identify key trends in methodological and theoretical areas and evidence-based findings drawn from empirical research that address the rich complexity of learning through the implementation of "Threshold Concepts" in the teaching of natural sciences.

2. Framework

In the context of the teaching of natural sciences, one of the fundamental challenges lies on discerning and understanding the meanings and perceptions that students have woven around their own interpretation of the world. This challenge amplifies when it comes to designing pedagogical activities that prompt a profound conceptual change about diverse natural phenomena (Mahmud & Gutiérrez, 2010).

These preexistent beliefs and perceptions, known as alternative conceptions, tend to be resistant to change and persist throughout the life of the individual. They are characterized by a coherent logical-causal structure and are influenced by the context. These conceptions do not differentiate between culture, gender, or ethnicity, demonstrating their universality in the learning process (Sanmartí, 2002). Therefore, it is imperative that pedagogical strategies used by teachers are designed to guide students towards conceptions that are aligned with scientific understanding (Resbiantoro & Setiani, 2022).

Systematic reviews related to alternative conceptions in the field of science highlight the fact that research centers greatly on implementation and diagnosis. However, there is a significant void in the study of the underlying cognitive components that propel conceptual change (Chavan & Khandagale, 2022; Resbiantoro & Setiani, 2022; Üce & Ceyhan, 2019).

In this scenario, the Threshold Concepts (TC) theory emerges as a promising proposal. It proposes that certain concepts possess an inherent power to radically transform the understanding and perspective of a student about a specific phenomenon (Knight, Budd, Bruehl & Pan, 2021). According to this theory, the educational process is seen as the fertile land of uncertainty, where these disciplinary concepts act as "portals", setting off metamorphosis in the way the apprentice perceives and understands various phenomena (Meyer & Land, 2003; 2005).

For those that are in the process of learning, the Threshold Concepts act as key instruments in these complex cognitive spaces of "blockage" or areas of uncertainty. In these spaces, students experience a fluctuation between previously established meanings and those that are emerging, deeply engaging their emotions in the process (Meyer, Land & Baillie, 2010). These Threshold Concepts are typically transformative, since they deeply alter the perception of the apprentice; irreversible, due to their lasting impact in the conceptual change; and integrative, since they facilitate the establishment of connections with other learnings and experiences (Ross et al., 2010). As Cousin (2006) points out, because of its transforming power in the experience of the student, Threshold Concepts should be considered essential in curricular construction.

The student's journey in the assimilation process of a Threshold Concept is visualized through the concept of liminality. As it is shown in Figure 1, liminality is described as a transforming event that includes various phases that are not linear. These phases are recursive and emotionally intricate (Hodge, 2019). The process initiates with a "pre-liminal" phase, in which the subject faces a disconnection, sometimes uncomfortable, with their previous knowledges and understandings, experiencing some kind of cognitive imbalance.

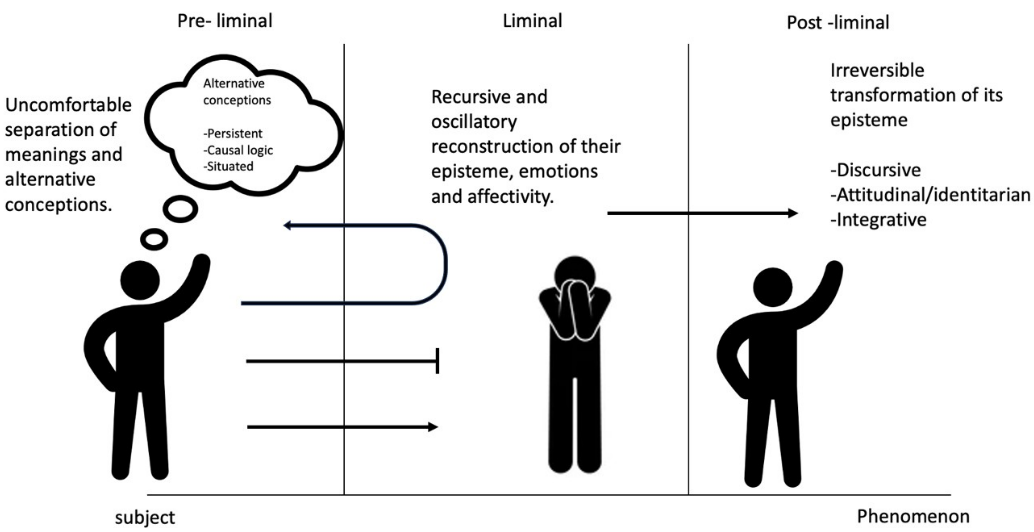

Figure 1. Schematic Model about liminal spaces (Walck-Shannon, Batzli, Pultorak & Boehmer,2019)

Then, in the "liminal" space, the student dives into a deep and fluctuating reconstruction of their perspective of the world. This phase is imbued with emotional and affective aspects and can also include questioning and transformations of the individual's identity. Finally, when reaching the "post-liminal" phase, the individual experiences an irreversible transformation of their discourse and their way of interpreting a given phenomenon and throws themselves into the exploration and establishing of new conceptual links (Meyer & Land, 2006).

Irrespective of the origin of alternative conceptions, there is no doubt that there is the challenge of delving into understanding the contribution of Threshold Concepts for the identification of alternative conceptions in natural sciences (Ross et al., 2010).

3. Methodology

The purpose of this systematic review is to identify trends about methodological and theoretical aspects and results about available evidence in empirical research between years 2018 to 2022 regarding Threshold Concepts in Natural Sciences. As a systematization method, the PRISMA 2020 declaration and its verification items (Page, McKenzie, Bossuyt, Boutron, Hoffmann, Mulrow et al., 2021) were used, since they offer a framework according to a mixed methodology, seeking to join quantitative elements typical of descriptive statistics (Rainkie, Abedini & Abdelkader, 2020; Abusaada & Elshater, 2022), as well as a thematic analysis of the selected articles. From this framework it is possible to identify trends in research fields, address questions that individual literature does not answer, and evaluate the impact of methodologies and theoretical constructs of interest (Page et al., 2021).

The systematic review is sustained in articles from 3 electronic databases: Web of Science (WOS), SCOPUS and Eric (see Table 1). The terms used in the databases were "Scientific Literacy", "Science Education" and "Threshold Concepts". The inclusion and exclusion criteria respond to the selection of open access empirical works, in English, Spanish or Russian in the context of natural science teaching (see Table 2).

Electronic Database	Boolean Operators
WOS/ SCOPUS	("Scien* literacy" OR "Scien* education" AND "Threshold concept*")
ERIC	("Scientific literacy" or "scientific education" and "threshold concepts")

Table 1. Boolean operators for the search of information in electronic databases

Inclusion criteria	Exclusion criteria
Empirical studies	Systematic reviews or meta-analysis
Open access	Books, editorials, theses, or conferences
Spanish, english, russian or portuguese language.	Works prior to 2018
Natural Sciences teaching contexts	Paid publications
Studies between 2018-2022	Contexts of non-scientific disciplines

Table 2. Inclusion and exclusion criteria

The PRISMA 2020 protocol is comprised by 27 phases that involve the selection, identification, sifting, analysis, and discussion of articles (Page et al., 2021). After the final selection, data of selected work is analyzed with tools from the Free Software, such as the *Research Rabbit* AI (https://researchrabbitapp.com/) for the construction of interactive bibliographic networks and *Bibliometrix* (https://www.bibliometrix.org) for the construction of thematic maps (Aria & Cucurullo, 2017).

4. Results

The sifting process for the performed search, according to the PRISMA 2020 protocol, is shown in Figure 2. A total of 280 articles were found: 265 ERIC articles, 11 from Web Science and 4 from Scopus. From these, 55 were rejected due to being duplicates and not eligible because of automatization tools.

During the review and eligibility phase, a total of 225 articles were available, of which 199 were excluded because of contents not associated to the topic of the teaching of natural sciences (for example: music, art, literature, or transportation engineering education), format of the articles, theses, systematic reviews, and paid publications. Finally, a total of 9 articles that complied with all the criteria were selected (see Table 3).

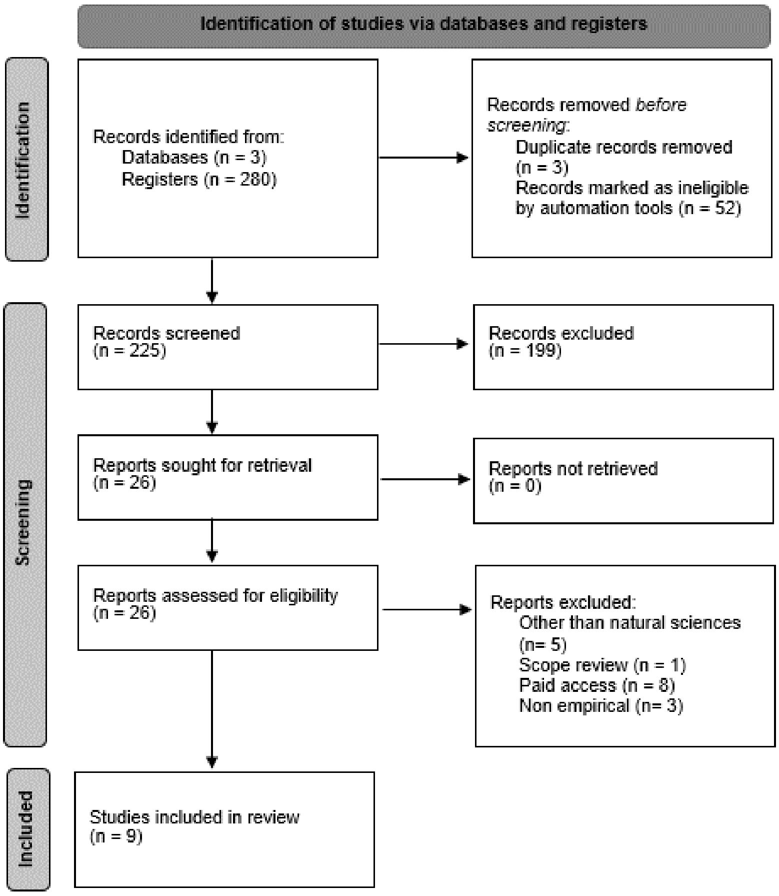

Figure 2. Identification of studies through databases and records, according to the Prisma 2020 declaration

From the sifting process described in the present review, we present the processing and categorization of the 9 resulting articles according to the Prisma 2020 selection criteria, including the work of Bohlin, Göransson, Höst & Tibell, 2017 that was included through the database, and was selected because of its methodological and bibliographic relevance. Of the results, it is possible to observe a predominance of publications from countries like the United States (4), Sweden (3) and in smaller proportions South Africa and Spain (1 each). It must be noted that all analyzed works are situated in higher education contexts (see Table 3).

Under the analysis of the Research Rabbit Artificial Intelligence instrument a mapping and record of existing interactions between the selected articles was performed (see Figure 3).

The map of Figure 3 is built from each gray line, which represents an existing quote between reference documents as blue nodes. The green nodes correspond to the corpus of connected articles between quotes to generate this bibliographic network, which allows to identify common references. The green spheres represent articles of the selected corpus, while the blue represent bibliographic references. The lines are coincident with those bibliographic similarities between authors. The app does not include the work of Lundqvist, Svensson, Ljung, Eriksson and Eriksson (2021), which will be discussed in the limitations section.

Authors	Educational level	Title of article	Type of research	Method or instrument	Natural Science area
Bennion et al.	University undergraduate	Asking the Right Questions: Using Reflective Essays for Experiential Assessment	Mixed	Essays, content analysis in comparison to 20 TC already published with concepts from history, biology, writing and recreational management.	Biology
Bohlin et al.	Not declared	A Conceptual Characterization of Online Videos Explaining Natural Selection	Quantitative	Content analysis with 28 criterion. The variables are supported by key concepts, TC, alternative conceptions, and organismic context. Each analyzed 33 videos, whose statistical reliability was subjected to the Krippendorff coefficient.	Biology
Ferreira et al.	University undergraduate	Alternative Conceptions: Turning Adversity into Advantage	Quantitative	Implementation test adapted from Force Concept Inventory (FCI) instruments and test on Energy and Movement.	Physics
Fredholm et al.	University	The Practice of Thresholds: Autonomy in Clinical Education Explored through Variation Theory and the Threshold Concepts Framework	Qualitative	Thematic analysis and narrative inquiry of challenged student stories and stories that allowed them to develop in their fields.	Health
Kang et al.	University undergraduate	Detecting Threshold Concepts through Bayesian Knowledge Tracing: Examining Research Skill Development in Biological Sciences at the Doctoral Level	Quantitative	Mapping of abilities and TC through the application of the system of Follow up – Partial Skills Transference as Continuous (BKT - PSTC), together with abilities rubrics.	Biology
Kopecki-Fjetland & Steffenson	University undergraduate	Design and Implementation of Active Learning Strategies to Enhance Student Understanding of Foundational Concepts in Biochemistry	Quantitative	Implementation of Instrument of Foundational Concepts for Biochemistry (IFCB) for alternative conceptions and surveys based on Likert appreciation scales.	Biochemistry
Lundqvist et al.	University undergraduate	A Phenomenographic Analysis of Students' Experience of Geological Time	Qualitative	Phenomenography through semi-structured interviews about geological times in swedish students.	Geology
Martin-Piedra et al.	University undergraduate	Identification of histological threshold concepts in health sciences curricula: Students' perception	Quantitative	Validation and application of the TC Histological Questionnaire (HTCq)	Biology
Walck-Shannon et al.	University undergraduate	Biological Variation as a Threshold Concept: Can We Measure Threshold Crossing?	Mixed	Semi-structured interviews coded over 4 dimensions of TC (discursive language, problematic explanations, liminal commentaries, and integration between multiple biological scales).	Biology

Table 3. Search result in SCOPUS, WOS, and ERIC databases

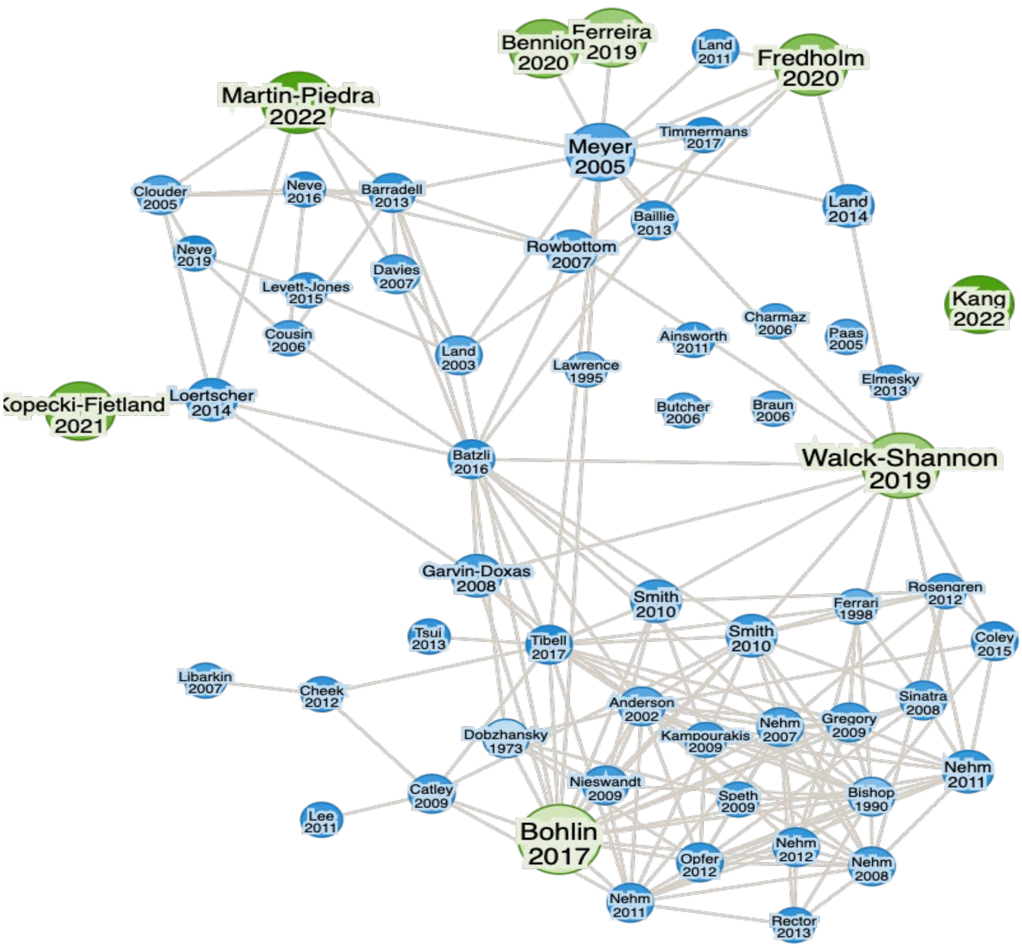

Figure 3. Mapping of Bibliographic interactions and connections between authors

The degree of similarity between the references of selected articles sheds light on the main leading authors on Threshold Concepts in the teaching of natural sciences, and theoretical, conceptual, and methodological trends. The seminal article of Meyer and Land (2005) is a convergent article, being quoted in 6 o 9 of the resulting journals.

About coincidences regarding bibliographic references, the works of Walck-Shannon et al. (2019) and Bohlin et al. (2017) have high density of bibliographic connections (5), while the work presented by Kang, Baker, Feng, Na, Granville and Feldon (2022), and Kopecki-Fjetland and Steffenson (2021) present smaller degrees of bibliographic similarities. In the intermediate region of the map, it is possible to observe the existence of inter-bibliographic examples such as the works of Meyer and Land (2003), Batzli, Knight, Hartley, Maskiewicz and Desy (2016) as well as Tibel and Harms (2017) with greater abundance of connections between bibliographic references in the field.

4.1. Trends about Threshold Concepts in Natural Sciences

Threshold Concepts have emerged with strength in the current educational scenario, and its influence in the natural sciences field is not an exception. These concepts, that act as catalysts of the learning process, have been identified as key turning points that transform the perception and understanding of students about specific phenomena. In the context of natural sciences, the current trends about Threshold Concepts point towards a deeper exploration of how these concepts can unleash significant conceptual changes, overcome previous misunderstandings, and connect thematic areas that are apparently dissimilar to offer a more holistic and enriching understanding of the natural principles. This Dynamic offers a promising scenario to redefine and improve pedagogical strategies in the teaching of sciences.

4.1.1. Research Purposes

In this present review, there is an evident predominance of empirical research with a quantitative focus, reflected in four works. On the other hand, a qualitative focus can be observed in three documents and a mixed methodology in two. A predominant trend is centered on identifying Threshold Concepts and is directed toward a purpose that is fundamentally diagnostic in relation to the alternative conceptions of undergraduate students. These investigations address areas such as biology (Martín-Piedra, Saavedra-Casado, Santisteban-Espejo, Campos, Chato-Astrain, Garcia-Garcia et al., 2023; Walck-Shannon et al., 2019), geology (Lundqvist et al., 2021) and even interdisciplinary approaches (Bennion, Cannon, Hill, Nelson & Ricks, 2020). It must be highlighted that the understanding of Threshold Concepts is not limited only to the traditional academic environment; it also extends to modern means, such as learning mediated by online videos, where alternative conceptions can arise (Bohlin et al., 2017).

On the other hand, a less noticeable trend is focused on the use of Threshold Concepts in longitudinal research. The objective of these studies is to decode these critical moments or inflection points that foster the transition of a student in training to an established professional, whether is during their practicums (Fredholm, Henningsohn, Savin-Baden & Silén, 2020), throughout doctoral programs (Kang et al., 2022) or during the course of a specific class (Bennion et al., 2020).

From this review, two methodological perspectives emerge clearly to address Threshold Concepts in the field of the natural sciences. A fraction of the investigations delves into the phenomenon to identify the specific Threshold Concepts in each discipline. Simultaneously, another group sets to analyze cognitive movements that students have to face, focusing on the liminal phases and epistemological transitions involved.

4.1.2. Research on Identification of Threshold Concepts

Bohlin et al. (2017) perform an analysis about the presence and characterization of Threshold Concepts available in videos about evolution in educational websites, showing the abundance of videos centered on evolutive phenomena at the individual level, a 75% of the total number. In contrast, those that center on aspects at the molecular level, such as genomes and molecules, are no higher than 30%. It is interesting to highlight that key concepts such as randomness and probability are predominantly transmitted in oral form. In addition, it’s infrequent to see transitions that cover three or more organization levels. These authors underscore the relevance of Threshold Concepts linked to “spatial scales” to decode evolutive aspects, such as structural analogies and homologies, and emphasize the need to delve into the quality of online educational videos.

Martín-Piedra et al. (2023) get deep into the perceptions of students of various health disciplines with the purpose of identifying concepts linked to histology, a fundamental subject for programs such as dentistry, medicine, and pharmacy. When analyzing the responses, it is observed that greater value is given to concepts related to morpho-structure and organization of tissue between dentistry students, while medicine and dentistry share a similar appreciation of the histo-functional organization. In addition, future doctors show a strong interest for information coming from 2-D microscopic sources. In the light of these findings, the importance of incorporating these instruments in undergraduate programs is suggested, leaving the door open to future validations in other languages and contexts.

Kopecki-Fjetland and Steffenson (2021) innovate by proposing an iterative methodology directed towards perfect alternative conceptions of students in a basic biochemistry course. After identifying such conceptions, specific activities were designed, which centered on problem-solving, tactile and synthesis activities. The results showed noticeable improvements, although significant differences between different strategies were not observed. However, surveys reflected a positive perception of students towards these methodologies.

On the other hand, Bennion et al. (2020) face the challenge of evaluating experiential elements in an interdisciplinary program. When analyzing essays from 17 students, they found agreements between the proposed ideas and the Threshold Concepts established in the literature, which supports the idea that certain concepts are broadly shared among the student community.

Regarding professional development, Fredholm et al. (2020) explore the crucial moments that shape autonomy and authenticity of health students in the context of Threshold Concepts and the Variation Theory Learning (VTL). The findings reflect that practical experiences tend to contrast with the previous theory, providing a special value to mistakes done in practical procedures.

Finally, Ferreira, Lemmer and Gunstone (2019) address student understanding about freefall and the influence of mass in gravitational acceleration. Their research reveals mistaken conceptions about movement phenomena, especially in atypical teaching contexts. This research highlights the need to correct these misunderstandings in order to guarantee an adequate understanding of basic physics.

4.1.3. Research on Cognitive Movement about Threshold Concepts

The concept of geological time is an essential Threshold Concept to understand spatial-temporal phenomena that is inherent to geology (Lundqvist et al., 2021). Through a phenomenographic design, four main categories were identified, which address the competences related to this concept. The first, called "narrative", describes how people express themselves when talking about geological time, whether it is from a personal or third person perspective. The second, "definition", refers to how geological time is characterized, whether in explicit or implicit form and can be represented as static, referring to specific processes, or flexible, adapting to different situations. The "contextualization" addresses how time is experienced or explored in relation to the dynamic of underlying phenomena. Lastly, "representation" encompasses linguistic and gestural elements or any other form of representing this Threshold Concept.

The objective of the Partial Skills Transference as Continuous model (BKT-PSTC) by Kang et al. (2022) is to understand the learning process and how skills that were acquired during the academic development can be transferred. This model identifies the nuances between different phases and evaluates the degree of skill transference at specific points of the academic program. Although it shows promise, a study concludes that it is a challenge to determine a specific point of inflection in the achievement of a Threshold Concept throughout its transition.

On the other hand, Walck-Shannon et al. (2019) explore different approaches to address Threshold Concepts, in particular the biological concept of "variation". For this, they used the "Think Aloud" method, which consists of verbalizing thoughts during the performance of a task. The responses were transcribed and coded according to a pre-defined set of discipline-specific terminology and the four dimensions associated to liminal transition: i) discursive, ii) problematic, iii) liminal and iv) integrative. The results reveal that the two more challenging dimensions of Threshold Concepts are those that require a detailed argumentation about the integration of multiple biological scales or disciplinary fields. Despite the complexity of distinguishing the threshold from the liminal, the study highlights the importance of identifying specific elements in the liminal space to enrich curricular design.

4.2. Instruments for Data Collection and Analysis

Table 2 shows the instruments used and the frequency with which they appear in the corpus of analyzed articles. It is noticeable that most of these instruments have a quantitative orientation, and in particular, designs that thrive are based in standardized questionnaires with specific focus in each discipline.

One of the prominent questionnaires is the Threshold Concepts in Histology (HTCq), which includes 37 relevant terms at the curricular level. These terms are evaluated through a Likert scale, which facilitates measuring student perceptions (Martín-Piedra et al., 2023). At the same time, the Foundational Concepts for Biochemistry instrument (IFCB) contains 21 questions distributed in seven essential dimensions: five linked to chemistry and two to biology (Villafañe, Bailey, Loertscher, Minderhout & Lewis, 2011). This tool has been quoted and contextualized by later investigations such as that of Kopecki-Fjetland and Steffenson (2021). In addition, the Inventory test of the Concept of Force (FCI), known by its ability to identify alternative conceptions in various contexts, considers several levels and movements (Ferreira et al., 2019).

In turn, semi-structured interviews have been consolidated as valuable tools to achieve a deep understanding of the variations in learning. They have been used to explore experiential events (Fredholm et al., 2020), as well as perceptions and understanding of students on topics such as "geological time" (Lundqvist et al., 2021) and the "Evolutive variation" (Walck-Shannon et al., 2019). The narratives produced by students, whether transversally or longitudinally, have been incorporated systematically to the analysis of learning processes (Fredholm et al., 2020; Bennion et al., 2020; Walck-Shannon et al., 2019; Kang et al., 2022).

Finally, one of the most notable innovations is the implementation of an algorithmic model known as Bayesian Knowledge Tracking (BKT). Developed originally for intelligent tutoring systems, it allows to model student knowledge in adaptative and simulated educational scenarios with precision (Sao-Pedro, Baker & Gobert, 2013). A recent variation, the Partial BKT of Skill Transference as Continuous (BKT-PTSC) is a step ahead, by capturing and analyzing the learning and skill transference processes through the different stages of student academic development (Kang et al., 2022).

Instrument	Frequency
Closed-question questionnaire	4
Interviews	3
Narrative productions	4
Appreciation surveys	1
Matrices	1
Algorithms	1

Table 4. Distribution of instruments declared by literature

Within the reviewed corpus, we found strong support of statistical techniques. However, when reviewing the information collected through interviews and documents, the predominance of content and thematic analysis is evident, being essential tools for the development and the interpretation of categories based on the relevant literature in each discipline. In addition, guidelines or rubrics have been used, based on the Threshold Concepts described in literature, in order to inductively identify the elements that are present in audiovisual resources (Bohlin et al., 2017) and in narratives produced by students throughout their learning process (Bennion et al., 2020; Walck-Shannon et al., 2019; Kang et al., 2022).

4.3. Conceptualizations Associated to Threshold Concepts

Among the corpus of the examined articles, different conceptualizations arise based on Threshold Concepts. These perspectives address cognitive transition and are intertwined in complementary form, illuminating inherent aspects of the learning of natural sciences. These aspects are linked to topics across the curriculum and highlight the importance of educational experiences in the learning process.

One of the current trends in international scientific education are the "Big Ideas of Science". These are presented as a unifying perspective and are understood as topics that extend across the curriculum, establishing connections between different phenomena (González-Weil & Bravo-González, 2018). This approach not only favors a deeper understanding, but also serves as scaffolding in the transition towards Threshold Concepts that promote understanding and transformation of phenomena (Tansey, Baird, Cox, Fox, Knight, Sears et al., 2013). Under the label of "Foundational Concepts", Kopecki-Fjetland and Steffenson (2021) have developed an innovative system that diagnoses alternative conceptions in chemistry. This system, applied in the biology curriculum, facilitates the creation of adequate didactic sequences, and allows to evaluate student progress throughout the semester.

On the other hand, learning experiences become significantly relevant in formative professional programs, especially in relation to practicums. The "Variation Theory of Learning" (VTL) emerges as an interactive framework where perception of a phenomenon expands from pure theory towards its dynamic and changing manifestations in an experiential context (Marton, 2014). This theory has been especially highlighted in research centered on experience-based teaching, as well as professional development in the heath field (Fredholm et al., 2020) or in travel logbooks during scientific expeditions (Lundqvist et al., 2021).

It is essential to underscore the valuable contribution that both perspectives offer to the understanding of Threshold Concepts. Their focus on curricular transversality provides a solid conceptual framework that fosters the understanding of a variety of natural phenomena. In addition, the acknowledgement of experiences, contexts, and multiple points of view regarding a specific phenomenon enriches and transforms the epistemological basis of student teachers. This richness and diversity translate into an opportunity to improve the curriculum with a broad spectrum of situations and challenges that students might face.

4.4. Main Topics of Interest about Threshold Concepts

Figure 4 presents an outlined thematic map, created through the Bibliometrix quantitative tool (Aria & Cucurullo, 2017). This map was built using the "keywords plus" of each article and is organized in three distinctive nodes. These nodes offer a panoramic view of the main topics of interest that converge among the different articles studied.

The links on the map symbolize the connections between keywords, grouping them in conglomerates identified by different colors. The cluster in red highlights higher education trends, especially oriented towards biological science, including both their knowledge as well as discipline practices. The blue cluster acts as an interconnection bridge and highlights the conceptualizations linked to Threshold Concepts, addressing them as epistemological tools and main sources of information. Finally, the green cluster focuses on concepts linked to methodologies and theoretical elements that explain the cognitive transition experienced by students during their learning process.

The density and relevance of each node in the map is reflected in its diameter and proximity to the center of the diagram. In particular, the nodes labeled "theoretical framework" and "students" stand out. These concepts, being frequently mentioned in the nine analyzed articles, take a central position in the map. In addition, it can be observed that both nodes have strong connections with the conglomerates that refer to epistemologies and methodologies, demonstrating their pivotal role in the general thematic structure of the corpus.

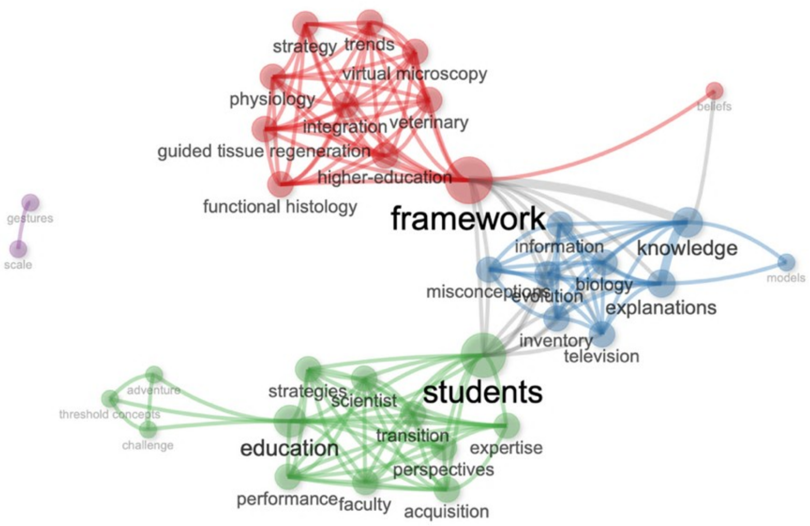

Figure 4. Thematic map

4.5. Main Threshold Concepts Declared by Literature

Within the corpus of examined articles, through a content analysis, five areas of knowledge linked to Natural Sciences have been identified: Biology, Health, Biochemistry, Geology and Physics. For each area, the emergent Threshold Concepts of each study have been characterized (see Table 5).

In this analysis, we observe a noticeable inclination towards terminology from the Biological Sciences domain, especially in relation to the evolution of species. Concepts such as "variation" (mentioned in three studies), "generational scales" (addressed in two articles) and "relationships between species" stand out. In addition, Threshold Concepts linked to the scientific method are incorporated, such as "replicability" and "control". In the health field and in agreement with the scientific nature of biological sciences, concepts such as "bio dimensional microscopy" and "tissue activity" stand out both in the biology area and the training of sanitary professionals, indicating a convergence between both areas.

On the other hand, in the field of Biochemistry, concepts such as "Acid Strength", "Bond energy" and "Chemical Equilibrium" emerge from one article and do not show intersections with other fields. In a similar way, the concepts of "Time", "representation" and "contextualization" are exclusive of the Geology field, while "Gravity" is distinctive to the Physics field.

Basically, trends point to a predominance of higher education investigations with a marked emphasis on biology and health, outshining other disciplines. Most articles tend to have a diagnostic focus to identify Threshold Concepts in natural sciences. However, there is a less addressed niche that includes longitudinal studies that seek to trace learning throughout a course of academic degree.

Together, the various works show a tendency to curricular design, centered on previous skills of students both at a conceptual and procedural level. This focus is considered essential to develop learning sequences that can adapt and respond to the needs of each group of students. Surprisingly, no studies that focused on the teacher's perspective and their interaction with students in the educational process were found.

The theoretical framework of Threshold Concepts is enriched with conceptualizations that add depth to its understanding, highlighting the importance of teaching phenomena in various contexts, which strengthens the learning experience proposed by the "Variation Theory of Learning" (VTL). This approach emphasizes the importance of establishing connections between natural phenomena, providing a scaffold for deep understanding.

Biology	**Health**	**Biochemistry**	**Geology**	**Physics**
Variation	Community	Acid Strength	Time	Gravity
Temporal scale	Society	Bond Energy	Contextualization	
Relationships	*Structural Morphology	Chemical Equilibrium	Representation	
Spatial scale	*Bidimensional microscopy	Free Energy		
Change/ Transition	*Tissue General Activity	Alpha-helix structures		
Randomness		Protein function		
Probability				
Differentiated Reproduction				
*Control				
*Replication				

Note: (*) Threshold Concepts related between Biology and Health areas

Table 5. Main areas and Threshold Concepts of examined articles

5. Discussion and Conclusions

A systematic review based on empirical research was performed around Threshold Concepts in the teaching of Natural Sciences. Following the PRISMA 2020 protocol, 280 articles were screened, resulting in the selection of nine appropriate works.

From a methodological standpoint we can highlight the contribution of AI based tools, which facilitated the identification of key concepts, and of a deep bibliographic analysis between selected authors. Through the use of open code tools, the democratization of knowledge and its access to it provides new spaces to delve into bibliometric characteristics that used to require greater efforts to analyze and now are available (Mahuli, Rai, Mahuli & Kumar, 2023). However, and in addition to the limitations presented in the limitations section, it is pertinent to consciously use these type of tools, given the ethical implications of AI generated tools (Hossain, 2024).

Placing Threshold Concepts and liminality at the center of attention represents a valuable opportunity to expand and improve perspectives about curricular and didactic models that are the foundation of Pedagogical Content Knowledge (PCK) of science teachers. From the performed analysis, Threshold Concepts that contribute to teaching have a rich methodological diversity, of instruments and concepts that explore the liminal transition of students.

In relation to the subjects of the studies, it is evident that researchers have omitted the elementary and secondary levels of education, focusing on higher education, both undergraduate and graduate. This trend agrees with other works that indicate the little attention towards these topics in initial educational levels (Thornton, 2020). However, it is crucial to acknowledge the importance of emotional commitment and the reflective spaces in children and teenagers, especially when they go through liminal stages in their learning process (Ashworth, 2016).

The reviewed articles reveal challenges when identifying these crucial moments in which students "cross the threshold" (Kang et al., 2022; Lundqvist et al., 2021; Walck-Shannon et al., 2019). The used methodologies center on evaluating competences in specific moments or, in some cases, in narratives that omit the emotional component, which is essential to propel the student through liminal phases (Meyer et al., 2010). This perspective emphasizes the need for a change in the way of addressing the student and acknowledging their active and emotional nature.

A more detailed and longitudinal study that seeks a better understanding of the learning evolution is proposed, incorporating class observations and other qualitative elements that reveal the real classroom dynamic (Fredholm, 2020; Bennion et al., 2020). There is research in science that recognizes the relevance of Threshold Concepts in curricular design, especially in higher education (Entwistle, 2008). For example, in biochemistry, concepts such as metabolic routes and thermodynamics are identified as Threshold Concepts in various disciplines (Loertscher, Green, Lewis, Lin & Minderhout, 2014).

However, many of the analyzed works are centered exclusively on student learning, omitting the role of the teacher in the process. This, combined with certain educational contexts, is an invitation to more research about the practices and perceptions of educators and how these can influence the transition of students towards a deeper understanding of the world. Regarding the research question that motivated this review, it is clear that the study of liminality and Threshold Concepts in Natural Sciences, especially considering the teacher-student relationship, is a field in expansion.

Therefore, it is necessary to delve into spaces that represent an opportunity within the classroom for the teacher to interpret these interactions with their students (Van Es & Sherin, 2002). This means considering social, emotional, and cognitive aspects in the class, making inferences regarding student learning (Barth-Cohen, Little & Abrahamson, 2018), where the construct of noticing appears as a prominent focus that allows "the act of observing or recognizing" (Jacobs, Philipp & Sherin, 2018: page 1) as it attends to, interprets, and responds to key situations in each session (Sherin, Jacobs & Philipp, 2011).

Noticing considers aspects of the exercised practice, aiming to make teachers aware of future opportunities and avoid practical mechanism (Mason, 2002). Systematic reviews report it as a viable methodology for the transformation of teacher practices of both in-service teachers and those in their initial training process (Weyers, König, Scheiner, Santagata & Kaiser, 2022; Santagata, König, Scheiner, Nguyen, Adleff, Yang et al., 2021; König, Santagata, Scheiner, Adleff, Yang & Kaiser, 2022), which is currently expanding to the teaching of natural sciences (Chan, Xu, Cooper, Berry & van Driel, 2021).

Considering that the main focus of the study of Threshold Concepts is in university professional teaching, visualizing aspects of teacher training, both initial and continuous for science teachers, is a feasible alternative to understand those "portals" that facilitate liminal movement of professionals in training.

As an alternative, under the teacher-student interactions, it is interesting to promote teacher reflection while considering, through *noticing*, those threshold elements of student learning. From the aforementioned, there are potential benefits in teacher performance for class planning, selection of methodologies and appropriate socio-scientific problems for each situated context.

It is essential to understand this interaction to transform the educational experience and promote a deeper understanding of the natural world in students, which considering the background and the results obtained, poses some questions such as ¿is it possible to understand the phenomena of Threshold Concepts and liminality in primary and secondary education? Given the nature of the school curriculum, ¿is it possible to integrate the Threshold Concepts view with the Natural Sciences contents? ¿How can the phenomena of liminality and Threshold Concepts contribute to in-service and initial training teachers?

Therefore, research on Threshold Concepts can lead to the development of new teaching strategies, such as the use of analogies, concrete examples, and multi-media approaches to clarify difficult concepts. This enhances the educational experience and makes learning more attractive and effective. In addition, research on Threshold Concepts can provide a firm basis for teacher education, allowing them to be better prepared to address the difficulties students may face. Educators can use this information to adapt their methods and approaches in the classroom.

5.1. Limitations of the Present Study

As a result of the performed review, we visualize the following limitations:

a) Scope of databases: Systematic reviews depend greatly on the consulted databases. If any relevant research is not indexed in these databases, they could be left out of the review.

b) Limitations of AI: The use of applications with bibliographic analysis purposes selected for the analysis phase, is subject to constant updates that seek to adjust key elements for the processing of the article corpus (Blaizot, Veettil, Saidoung, Moreno-Garcia, Wiratunga, Aceves-Martins et al., 2022). This is seen in the inter-bibliographic analysis phase, which did not include one of the selected works. In the same way, selected search engines from the databases included an article outside the temporal inclusion criteria, but given its relevance, it was selected within the article corpus (Bohlin et al., 2017).

c) Publishing bias: There is the possibility that studies with significant or positive results are published with greater frequency than those with negative or non-conclusive, which can have an impact in the findings of the review.

d) Methodological Diversity: Studies included can have different methodologies, sample populations and contexts, which can complicate the synthesis and direct comparison of findings.

e) Temporal lines: Since systematic reviews are based on existing literature until a specific date, any relevant investigation published after this date is excluded.

f) Language and regionality: The review can be limited to published studies in certain languages or regions, which could omit valuable perspectives and findings from other geographic areas or cultures.

g) Subjective interpretation: Despite the systematic nature of the review, the inclusion or exclusion of studies and the interpretation of data can be subjected to interpretation and the judgement of the researcher.

5.2. Projections of the Present Study

As a result of the performed review, we visualize the following projections and continuity:

a) Incorporating new methods: As new methods and approaches to study Threshold Concepts emerge, future reviews may include and evaluate these approaches, enriching the understanding of the topic.

b) Interdisciplinary study: Given the interdisciplinary nature of Threshold Concepts, we anticipate that future reviews could integrate investigations of various disciplines, to offer a more holistic vision.

c) Geographic and cultural expansion: Future reviews could strive to include studies from different regions and cultures, providing a more global understanding of how Threshold Concepts are perceived and taught in different contexts.

d) Focus on practical applications: As the field matures, we can expect the rise of more research centered on practical applications and didactic strategies related to Threshold Concepts, which will be key for their effective incorporation to the classroom.

e) Integration of emergent technologies: With the rapid evolution of educational technology, future reviews could explore how digital tools and platforms can influence or be used to better teach and understand Threshold Concepts.

f) Institutional collaborations: The increasing importance of Threshold Concepts can promote collaborations between institutions, which could result in multi-centered studies and broader and stronger reviews in the future.

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