Beyond Citations: An Epistemic Framework for Evaluating the Knowledge Structure of Scientific Articles

Siarhei Kandrychyn
Independent Researcher kandryczs@gmail.com

Abstract

Scientific articles constitute the primary unit of communication in modern science, yet evaluating their epistemic contribution remains challenging. Existing approaches, including peer review and citation-based metrics, capture only selected aspects of scientific value and provide limited insight into the internal structure of scientific knowledge. This study proposes a multidimensional epistemic framework for analysing the knowledge structure and potential impact of scientific publications. The framework consists of three complementary indices: the Conceptual Density Index (CDI), reflecting the structured development of scientific reasoning within an article; the Thematic Novelty Index (TNI), describing the extent to which a study introduces novel research themes or conceptual directions; and the Knowledge Integration Index (KII), capturing the degree to which the article integrates knowledge across conceptual or disciplinary boundaries. Together, these indices capture key mechanisms of scientific development: the structuring of scientific reasoning, the emergence of new research themes, and the integration of knowledge across domains. Their interaction can be represented through aggregated indicators describing the overall epistemic configuration of a scientific article. The proposed framework provides a simple epistemic scientometric tool for analysing scientific publications and may support future research on the structural evaluation of scientific knowledge beyond traditional citation-based metrics.

Keywords scientometrics; epistemic structure; research evaluation; knowledge integration; scientific communication; epistemic indicators

List of Abbreviations

Abbreviation — Definition
CDI — Conceptual Density Index
TNI — Thematic Novelty Index
KII — Knowledge Integration Index
EI — Epistemic Index
EE — Epistemic Energy
AI — Artificial Intelligence

1.Introduction

Scientific articles constitute the primary unit of communication in modern science. Yet evaluating their epistemic contribution remains challenging, as existing approaches—such as peer review and citation-based metrics—capture only selected aspects of scientific value.

The cumulative development of scientific knowledge depends largely on the reliability, clarity, and epistemic value of published contributions, as well as on the institutional norms governing scientific communication (Kuhn 1970; Merton 1973). For researchers, clinicians, and policy makers, academic publications therefore serve not only as records of research activity but also as primary media through which knowledge is evaluated, transmitted, and integrated into broader intellectual frameworks (Popper 1959).

Because of this central role, assessing the quality and credibility of academic publications constitutes a crucial component of the scientific enterprise. Decisions concerning publication, funding, academic promotion, and the application of research findings in clinical or policy contexts frequently depend on evaluations of individual studies. Ideally, such assessments should consider not only the novelty of the findings but also the conceptual depth of the argument, the methodological soundness of the study, and the coherence between evidence and interpretation. In practice, however, the reliability and reproducibility of published results have been widely debated in the meta-research literature (Ioannidis 2005; Altman 1994).

The most widely used mechanism for assessing scientific work is peer review. In principle, peer review enables experts within a given field to evaluate the methodological rigour, originality, and relevance of submitted manuscripts. Despite its central role in scientific publishing, peer review has well-recognised limitations. Reviews may vary substantially between reviewers, evaluation criteria are often implicit rather than formally defined, and judgments may depend on disciplinary conventions or subjective interpretations (Bornmann 2011). As a result, although peer review remains indispensable, its outcomes are often difficult to standardise or reproduce.

Alongside peer review, bibliometric indicators are widely used to estimate the influence or significance of scientific work. Citation counts, journal impact factors, and metrics such as the h-index (Garfield 1955; Hirsch 2005; Waltman 2016) are commonly employed to compare the impact of articles, journals, or researchers. These indicators provide valuable information about patterns of scientific dissemination and influence. However, bibliometric measures primarily capture the external reception of a publication rather than its internal epistemic structure. An article may be widely cited for reasons that are only partially related to its conceptual clarity or evidential robustness (Bornmann and Daniel 2008), while studies of substantial methodological or theoretical value may receive relatively limited citation attention.

These limitations highlight the need for complementary approaches that focus on the internal organisation of scientific texts. Academic publications are not merely collections of results; they are structured arguments in which conceptual ideas, empirical evidence, and logical reasoning interact. Examining how these components are organised within a paper may provide additional insight into the epistemic quality of the research being presented. Nevertheless, relatively few frameworks exist that allow such structural and epistemic characteristics to be described in a systematic and transparent manner (Ioannidis 2018; Bornmann 2011).

Recent progress in artificial intelligence, particularly in large language models capable of processing extensive textual corpora, has created new possibilities for the systematic analysis of scientific literature (Brown et al. 2020; Bommasani et al. 2021; Yu et al. 2018). If automated systems are to assist in evaluating, summarising, or navigating scientific publications, they require interpretable analytical components that capture meaningful aspects of scholarly reasoning rather than relying solely on superficial textual features.

In this context, a multidimensional framework that integrates structural, conceptual, and evidential aspects of scientific articles may provide a useful analytical perspective. By distinguishing between different components of epistemic organisation, such a model may help clarify how knowledge claims are constructed, supported, and communicated within research publications.

To address these limitations, this study introduces a multidimensional framework for analysing the epistemic structure of academic publications. The proposed model is based on three complementary analytical components: the Conceptual Density Index (CDI), the Thematic Novelty Index (TNI), and the Knowledge Integration Index (KII). These indicators are author-defined constructs, conceptually informed by prior work in philosophy of science and scientometrics (Kuhn 1970; Merton 1973; Waltman 2016; Ioannidis 2018), but are not derived from existing bibliometric measures. Together, they capture key mechanisms through which scientific knowledge develops within research publications, including the density of conceptual structures, the emergence of novel research themes, and the integration of knowledge across conceptual or disciplinary domains.

The framework adopts an epistemic scientometric perspective that links the internal organisation of scientific reasoning within research articles to their potential long-term influence in the scientific literature. The primary objective of the study is methodological: to develop and formally describe a structured analytical framework for examining the epistemic structure of scientific texts. The empirical analyses presented in later sections serve primarily as illustrative demonstrations of the analytical behaviour and interpretative potential of the proposed model. By focusing on the internal epistemic organisation of scientific texts, the proposed framework contributes to the development of a complementary perspective in scientometrics that extends beyond citation-based indicators.

2. Conceptual Framework

The proposed framework evaluates the epistemic structure of scientific publications through three complementary analytical dimensions: conceptual structure, thematic novelty, and knowledge integration. These dimensions are operationalised through three indices: the Conceptual Density Index (CDI), the Thematic Novelty Index (TNI), and the Knowledge Integration Index (KII).

Together, these indices capture key mechanisms through which scientific knowledge evolves, including the structuring of scientific reasoning, the emergence of new research themes, and the integration of knowledge across conceptual or disciplinary boundaries.

2.1 Conceptual Density Index (CDI)

The Conceptual Density Index (CDI) quantifies the conceptual structure of a scientific article and reflects the extent to which a study presents a coherent and logically organised development of scientific reasoning.

Scientific publications typically follow a structured intellectual progression in which a research problem is defined, a knowledge gap is identified, a hypothesis is formulated, and findings are interpreted within a broader theoretical context. The CDI captures the degree to which this conceptual progression is explicitly articulated within the structure of the article. In this sense, CDI can be interpreted as an approximation of the internal cognitive architecture of scientific reasoning as expressed in written form.

The CDI consists of five components corresponding to key stages of conceptual development in scientific reasoning:

• **Problem Formulation (PF)** – evaluation of how clearly the article formulates the central research problem and defines the scope of the investigation.

• **Knowledge Gap Exposition (KGE)** – assessment of whether the article explicitly identifies gaps or limitations in existing knowledge.

• **Hypothesis Articulation (HT)** – evaluation of whether the study formulates clear theoretical or empirical expectations linking the research problem with anticipated findings.

• **Discovery or Key Finding (DI)** – identification of the principal empirical or conceptual contribution presented in the article.

• **Interpretative Integration (II)** – assessment of the extent to which findings are interpreted within a broader theoretical or practical context.

Each component is evaluated using an ordinal scale ranging from 0 to 3, where higher values indicate a stronger presence of the corresponding conceptual element.

The total CDI score is calculated as:

$$CDI = PF + KGE + HT + DI + II$$

The CDI therefore represents a quantitative approximation of the conceptual structure of scientific reasoning within an article.

2.2 Thematic Novelty Index (TNI)

The Thematic Novelty Index (TNI) evaluates the degree of conceptual innovation introduced by a scientific article. While the Conceptual Density Index (CDI) captures the internal structure of scientific reasoning, the TNI focuses on the extent to which a study contributes new research themes, theoretical perspectives, or conceptual directions to the scientific literature.

The index assesses the originality of the research question and its conceptual positioning within the existing body of knowledge. Scientific progress often emerges through the introduction of new conceptual frameworks or reinterpretations of empirical observations.

The TNI consists of three components:

• **Conceptual Originality (CO)** – evaluation of whether the article introduces new concepts, models, or theoretical approaches.

• **Hypothesis Novelty (HN)** – assessment of the originality of theoretical propositions or hypotheses formulated in the study.

• **Paradigm Relevance (PR)** – evaluation of the potential of proposed ideas to influence broader theoretical frameworks or stimulate new lines of research.

Each component is evaluated using an ordinal scale ranging from 0 to 3.

The total TNI score is calculated as:

TNI = CO + HN + PR

The TNI therefore represents a quantitative approximation of the degree of theoretical innovation contained in a scientific article.

2.3 Knowledge Integration Index (KII)

The Knowledge Integration Index (KII) evaluates the extent to which a scientific article integrates knowledge across conceptual or disciplinary boundaries. Scientific progress frequently occurs through the synthesis of ideas originating in different domains of knowledge. Articles that successfully connect concepts, methods, or perspectives from multiple fields may therefore play an important role in advancing interdisciplinary understanding.

The KII measures the degree to which a study contributes to such epistemic integration through three components:

• Interdisciplinary References (IR) – the extent to which the article draws upon literature from multiple scientific disciplines.

• Conceptual Synthesis (CS) – the extent to which the study integrates different conceptual frameworks or theoretical perspectives.

• Cross-Field Relevance (CR) – the extent to which the findings have implications beyond the immediate field in which the research was conducted.

Each component is evaluated using an ordinal scale ranging from 0 to 3. The total KII score is calculated as:

KII = IR + CS + CR

The KII therefore reflects the degree to which a scientific article contributes to the integration of knowledge across disciplinary or conceptual boundaries. These components involve a degree of interpretative assessment and are therefore subject to expert judgement, despite being guided by a structured scoring protocol.

2.4 Integral Representation of Article Value

The indices CDI, TNI, and KII constitute the primary epistemic indicators derived from the structural analysis of scientific texts. Together, they capture three complementary dimensions of knowledge production: conceptual development of ideas (CDI), thematic innovation (TNI), and the integration of knowledge across domains (KII).

The proposed indicators are constructed on the basis of bibliographic reference data. While they draw conceptually on established approaches to diversity, novelty, and knowledge integration, their operationalisation and integration into a unified epistemic framework represent an original contribution of this study. Unlike prior approaches that typically focus on single dimensions of scientific output, the proposed framework captures the multidimensional epistemic structure of scientific reasoning.

To obtain a synthetic representation of the epistemic profile of a scientific article, these indices may be combined into aggregated measures. Formally, the epistemic profile can be expressed as a multidimensional vector (CDI, TNI, KII), whose scalar transformations yield composite indicators of epistemic structure. The proposed approach should be understood as a structured exploratory framework with operationalised indices.

A preliminary application of the framework was conducted on a pilot set of articles to assess its analytical consistency and interpretability. The results suggest that the indices differentiate between articles with varying levels of conceptual development and thematic novelty.

2.4.1 Additive Representation: Epistemic Index (EI)

The simplest integral representation of article value is the additive combination of the three indices:

EI = CDI + TNI + KII

This distinction is analytical in nature and does not preclude the possibility of empirical correlations between the indices. Formally, the additive formulation assumes linear independence of the three components, such that each contributes separately to the resulting epistemic score.

The Epistemic Index (EI) represents the overall epistemic configuration of a scientific article derived from the additive combination of the three component indices. As such, EI provides a stable and readily interpretable indicator of the epistemic profile of a scientific text.

In the present study, EI serves as the primary comparative indicator, allowing epistemic profiles of different articles or disciplinary groups to be systematically compared.

2.4.2 Multiplicative Representation: Epistemic Energy (EE)

In addition to the additive representation, a multiplicative combination of the indices may also be employed:

EE = CDI × TNI × KII

This composite indicator is referred to as *Epistemic Energy (EE)*. Unlike the additive formulation, the multiplicative approach emphasises the interaction between the three epistemic dimensions. The term “Epistemic Energy” is used metaphorically to denote the intensity of interaction between these dimensions rather than a physical quantity.

High values of EE are observed when conceptual density, thematic novelty, and knowledge integration are simultaneously well developed within a scientific article. Due to its multiplicative structure, the indicator is sensitive to low values of individual components, thereby emphasising the importance of a balanced development across all three epistemic dimensions.

2.4.3 Interpretation within the Framework

Within the proposed framework, the three indices provide complementary information about the epistemic characteristics of scientific publications. The Conceptual Density Index (CDI) reflects the internal structure of scientific reasoning and the extent to which key elements of the research process—problem formulation, hypothesis articulation, empirical findings, and interpretative integration—are clearly articulated. The Thematic Novelty Index (TNI) captures the originality of the research theme and evaluates the extent to which a study introduces new conceptual directions, hypotheses, or theoretical perspectives. The Knowledge Integration Index (KII) describes the degree to which knowledge originating from different conceptual or disciplinary domains is integrated within the article.

Together with the aggregated indicators Epistemic Index (EI) and Epistemic Energy (EE), these measures allow the multidimensional epistemic structure of scientific articles to be represented in a concise quantitative form while preserving the interpretability of individual components. Detailed operationalisation of the CDI–TNI–KII framework, including scoring schemes and normalisation procedures, is provided in the Supplementary Materials (Table S1). Within this methodological perspective, the framework is intended not as a direct predictor of citation counts, but as an analytical tool for systematically characterising the epistemic structure of scientific articles using a set of explicitly defined indicators.

2.4.4 Interpretation of Index Values

For comparative analyses, the values of CDI, TNI, and KII may be expressed on a normalised scale ranging from 0 to 10. This common scale facilitates comparison across articles and disciplinary contexts.

In general terms:

0–3 indicate limited presence of the analysed epistemic dimension;
4–6 reflect a moderate level of conceptual development, thematic novelty, or interdisciplinary integration;
7–10 indicate a strong and clearly articulated presence of the corresponding dimension.

These ranges should be interpreted as heuristic guidelines rather than strict thresholds, as the distribution of index values may vary between disciplines.

2.4.5 AI-assisted evaluation

Within the CDI–TNI–KII framework, the evaluation of structural and conceptual components of academic publications may be supported by automated text analysis. Artificial intelligence systems can identify key elements of scientific discourse, including research questions, knowledge gaps, hypotheses, empirical findings, and interpretative passages.

Such automated detection can assist in preliminary scoring of the indices by systematically locating structural and conceptual features within the text.

However, AI-based analysis cannot be considered epistemically neutral. Language models rely on patterns derived from previously published literature and may reproduce prevailing disciplinary conventions and interpretative biases. For this reason, automated analysis should be regarded primarily as a methodological instrument supporting the analytical process rather than as an autonomous evaluator.

Within the framework proposed in this study, AI is used for the initial identification of textual structures relevant to CDI, TNI, and KII. Human verification may be required when assessing conceptual novelty, the significance of knowledge gaps, or the broader epistemic relevance of research findings.

The methodological implementation of AI-assisted evaluation is described in Supplementary Table S2.

3. Methods

3.1 Study design

This study introduces a methodological framework for the structured evaluation of scientific articles based on three complementary epistemic dimensions: conceptual development of scientific reasoning, thematic novelty of the research problem, and knowledge integration within the broader structure of scientific knowledge. These analytical components are operationalised through three indices: the **Conceptual Density Index (CDI)**, the **Thematic Novelty Index (TNI)**, and the **Knowledge Integration Index (KII)**.

The aim of the framework is to analyse the internal epistemic architecture of academic publications independently of traditional post-publication metrics such as citation counts. Rather than relying on bibliometric indicators, the model evaluates structural characteristics of scientific texts, including conceptual reasoning, thematic originality, and the degree to which findings contribute to cumulative scientific knowledge.

The framework is intended as an exploratory analytical tool enabling systematic comparison of academic publications and providing insight into the mechanisms of knowledge construction within scholarly communication.

3.2 Conceptual structure of the model

Within the proposed framework, each scientific article can be represented as a point in a three-dimensional epistemic space defined by the indices CDI, TNI, and KII. These indices correspond to three complementary aspects of scientific communication:

1.conceptual density of scientific reasoning

2.thematic novelty of the research problem

3.integration of findings into the broader knowledge structure

Formally, an article may be represented as a vector:

A = (CDI, TNI, KII)

This representation enables scientific articles to be positioned within a multidimensional epistemic space and allows comparative analysis of their knowledge-structure profiles.

Although conceptual development and thematic novelty may influence the integration of knowledge within a scientific contribution, the Knowledge Integration Index (KII) is operationalised in the present framework as an independent structural indicator. Specifically, KII is assessed through three analytical components: interdisciplinary references, conceptual synthesis, and cross-field relevance.

The conceptual structure of the proposed framework is illustrated in Figure 1.

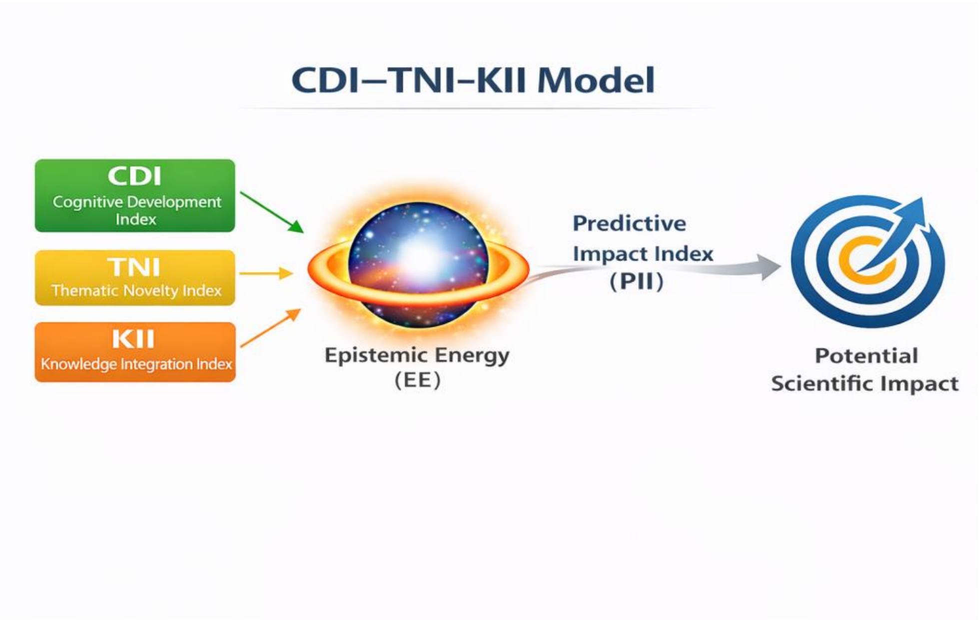

Figure 1. Conceptual structure of the CDI–TNI–KII epistemic evaluation model. The framework integrates three analytical indices of academic publications: the Conceptual Density Index (CDI), the Thematic Novelty Index (TNI), and the Knowledge Integration Index (KII). Their interaction characterises the epistemic configuration of a publication.

Within this framework, the interaction between conceptual development (CDI), thematic novelty (TNI), and knowledge integration (KII) may be interpreted as the epistemic profile of a scientific article. The combined effect of these indices can be represented by the Epistemic Energy (EE) of a publication, reflecting the structural balance of its epistemic components.

Articles characterised by strong conceptual development, thematic novelty, and knowledge integration may therefore exhibit greater potential for long-term scientific influence. Within the proposed framework, this potential influence may be reflected in the aggregated epistemic indicators EI and EE. Although citation dynamics depend on many external factors—including disciplinary conventions, visibility, and collaboration networks—the model assumes that publications characterised by stronger epistemic structure and more coherent scientific reasoning have a higher probability of generating sustained scholarly influence.

Such a multidimensional representation of scientific articles is consistent with broader scientometric approaches that seek to analyse the structure of scientific knowledge beyond simple citation counts or traditional bibliometric indicators (Garfield 1955; Hirsch 2005; Waltman 2016; Bornmann and Daniel 2008). By integrating conceptual, thematic, and integrative dimensions, the CDI–TNI–KII framework provides a structured analytical perspective for examining the epistemic architecture of publications and their potential role in the development of scientific knowledge.

3.3 Epistemic indices

3.3.1 Conceptual Density Index (CDI)

The **Conceptual Density Index (CDI)** evaluates the internal structure of scientific reasoning. Conceptual density refers to the structured progression of argumentation through which a research problem is defined, a knowledge gap is identified, a hypothesis is formulated, empirical findings are presented, and the results are interpreted within a broader conceptual context.

Five components are evaluated: problem formulation (PF), knowledge gap exposition (KGE), hypothesis articulation (HT), discovery or key finding (DI), and interpretative integration (II). Each component is scored on an ordinal scale from **0 to 3**, and the CDI score is calculated as:

CDI = PF + KGE + HT + DI + II

The theoretical maximum value of **CDI is 15**.

3.3.2 Thematic Novelty Index (TNI)

The **Thematic Novelty Index (TNI)** measures the originality of the research theme and the extent to which an article introduces new conceptual directions within a field. The index reflects whether the study proposes new conceptual perspectives, novel hypotheses, or research questions with potential relevance for disciplinary development.

Three components are evaluated: conceptual originality (CO), hypothesis novelty (HN), and paradigm relevance (PR). Each component is scored from **0 to 3**, and the index is calculated as:

TNI = CO + HN + PR

The theoretical maximum value of **TNI is 9**.

3.3.3 Knowledge Integration Index (KII)

The Knowledge Integration Index (KII) evaluates the extent to which the findings of an article are integrated into the broader structure of scientific knowledge. While the Conceptual Density Index (CDI) and the Thematic Novelty Index (TNI) assess internal reasoning and thematic originality, KII reflects the potential contribution of a study to cumulative knowledge.

Three components are evaluated: interdisciplinary references (IR), conceptual synthesis (CS), and cross-field relevance (CR). Each component is scored from 0 to 3, and the index is calculated as:

$$KII = IR + CS + CR$$

The theoretical maximum value of KII is 9.

The Knowledge Integration Index (KII) therefore captures the extent to which a study connects its findings with broader theoretical frameworks and integrates knowledge across disciplinary boundaries.

Although conceptual development and thematic novelty may influence the degree to which research findings are integrated within the broader scientific literature, the Knowledge Integration Index (KII) is operationalised in the present framework as an independent analytical indicator.

Importantly, this formalisation is not intended to replace peer review or expert judgement. Rather, the framework should be understood as a complementary analytical tool. Quantitative or semi-quantitative indicators such as the three indices of the framework (CDI, TNI, and KII) may help identify patterns across large collections of articles, support comparative analyses between journals or disciplines, and contribute to broader studies of scientific communication and citation behaviour (Waltman 2016; Bornmann and Daniel 2008).

The framework also opens several directions for future research. One natural extension would involve applying the CDI–TNI–KII model to large bibliographic datasets in order to explore statistical relationships between conceptual density, thematic novelty, knowledge integration, and indicators of scientific impact such as citation counts or the long-term influence of research findings (Ioannidis 2018; Waltman 2016). Another promising direction concerns the use of natural language processing and artificial intelligence tools to assist in the automated estimation of CDI, TNI, and KII, potentially enabling large-scale analysis of thousands of scientific texts (Brown et al. 2020; Bommasani et al. 2021; Yu et al. 2018).

Further methodological work will also be required to refine the operational definitions of the indices and to validate them across different scientific fields. Disciplines differ substantially in their conventions of writing, methodological reporting, and conceptual framing, and these differences may influence the behaviour of the proposed indicators.

From a broader perspective, the proposed framework also suggests a possible interpretation of scientific influence: citations may be understood as the delayed diffusion of epistemic structures within the scientific literature. In this interpretation, articles characterised by strong conceptual density (CDI), high thematic novelty (TNI), and effective knowledge integration (KII) may generate stronger epistemic configurations that subsequently propagate through citation networks as their ideas are adopted and developed by later research (Waltman 2016; Bornmann and Daniel 2008).

The CDI–TNI–KII framework therefore provides not only a quantitative indicator of epistemic contribution but also a structural profile of how scientific knowledge is generated and integrated across disciplines.

3.4 Integral representation of epistemic structure

The indices **CDI**, **TNI**, and **KII** constitute the primary indicators derived from textual analysis. Two aggregated measures are used to characterise the overall epistemic profile of an article.

The additive epistemic score is defined as:

EI = CDI + TNI + KII

A complementary multiplicative indicator, referred to as **Epistemic Energy (EE)**, captures the interaction between the three epistemic indices:

EE = CDI × TNI × KII

Because the formulation is multiplicative, a low value in any dimension substantially reduces the overall interaction score. Within the framework, EI serves as the principal comparative indicator, whereas EE provides complementary information about the balance between epistemic components.

3.5 AI-assisted evaluation procedure

The evaluation procedure may be supported by automated analysis of scientific texts using artificial intelligence. AI systems assist in identifying structural elements of scientific discourse, including research questions, knowledge gaps, hypotheses, empirical findings, and interpretative sections.

In the proposed workflow, AI performs an initial structural analysis and identifies candidate textual segments corresponding to the components required for calculating **CDI**, **TNI**, and **KII** scores.

3.6 Human supervision and interpretative validation

Certain components require contextual interpretation and domain expertise that cannot be reliably inferred through automated text analysis alone. In particular, the evaluation of conceptual novelty, the significance of knowledge gaps, and the broader integration of research findings may require expert judgement.

The framework therefore adopts a hybrid evaluation approach in which AI-assisted structural detection is complemented by human supervision when interpretative assessment is required.

3.7 Analytical interpretation

The resulting CDI, TNI, and KII scores enable the construction of multidimensional epistemic profiles of scientific articles. By representing articles as points in a three-dimensional epistemic space, the framework allows comparison of conceptual density, thematic novelty, and knowledge integration across studies and may support future research on the structural characteristics of influential scientific publications.

It should be noted, however, that the scoring procedure involves a degree of interpretative judgement. Although formal inter-rater reliability testing was not conducted, the structured scoring protocol was designed to minimise subjective variability.

4. Illustrative analysis

4.1 Demonstration of the CDI–TNI–KII framework

To demonstrate the practical applicability of the proposed framework, an illustrative analysis of selected scientific publications was conducted using the CDI–TNI–KII model. The aim of this exercise is not to produce definitive empirical conclusions but rather to demonstrate the operational logic of the proposed epistemic indicators. Illustrative analyses of this type are commonly used in methodological research in scientometrics and meta-research to clarify how newly proposed analytical frameworks may be applied to the evaluation of scientific literature.

For this demonstration, a small sample of highly cited publications from several scientific disciplines was examined. The selected works characterise influential contributions in fields including philosophy, sociology, scientometrics, physics, chemistry, molecular biology, and medicine together with selected clinical subfields. The analysis focuses primarily on publications from the period 1990–2015, allowing observation of epistemic characteristics across several decades of modern scientific publishing.

Within each discipline, approximately twenty highly cited papers were selected as reference material. The purpose of this selection was not to construct a comprehensive bibliometric dataset but rather to provide an illustrative empirical basis for demonstrating the practical application of the proposed epistemic indicators across different domains of scientific research.

Each publication was evaluated using the three indices defined in this study: the Conceptual Density Index (CDI), the Thematic Novelty Index (TNI), and the Knowledge Integration Index (KII). The evaluation procedure consisted of qualitative reading combined with interpretative scoring of structural and conceptual characteristics of the analysed publications. The resulting scores should therefore be interpreted as illustrative epistemic estimates rather than precise quantitative measurements.

To explore the behaviour of the framework across broader disciplinary contexts, mean values of the three epistemic indicators were estimated for each field. Articles were identified through queries in bibliographic databases and selected using randomised sampling within the defined disciplinary categories. The resulting comparative profiles are presented in Table 1. Differences between highly cited publications and randomly selected recent articles are summarised in Supplementary Table S1, while additional comparative statistics are reported in Supplementary Table S2.

Table 1. Mean epistemic indices across scientific fields. Values characterise mean scores for highly cited papers (1990–2015), with values for randomly selected papers (2016–2025) shown in parentheses.

Field	CDI	TNI	KII	EI	EE
Philosophy	9.14 (8.19)	9.08 (8.12)	9.01 (8.32)	27.23 (24.63)	752 (553)
Sociology	8.50 (7.80)	8.40 (7.70)	8.70 (8.00)	25.60 (23.50)	620 (480)
Scientometrics	8.76 (7.95)	8.69 (7.83)	9.05 (8.34)	26.50 (24.12)	690 (520)
Physics	9.30 (8.50)	9.10 (8.30)	9.20 (8.60)	27.60 (25.40)	780 (605)
Chemistry	9.00 (8.30)	8.80 (8.10)	9.10 (8.50)	26.90 (24.90)	720 (572)
Molecular biology	9.28 (8.54)	9.22 (8.51)	9.42 (8.82)	27.92 (25.87)	812 (646)
Medicine	8.98 (7.92)	8.86 (7.78)	9.16 (8.34)	27.00 (24.04)	727 (512)
Epidemiology	8.85 (7.90)	8.75 (7.80)	9.05 (8.30)	26.65 (24.00)	700 (510)
Cardiology	9.03 (8.18)	8.93 (8.08)	9.27 (8.45)	27.23 (24.71)	748 (557)
Surgery	8.82 (7.97)	8.74 (7.89)	9.07 (8.26)	26.63 (24.12)	699 (514)
Pediatrics	8.83 (7.96)	8.72 (7.88)	9.12 (8.25)	26.67 (24.09)	704 (512)

Table notes Values represent mean epistemic scores derived from the CDI–TNI–KII framework. For each indicator, the first value corresponds to highly cited papers published between 1990 and 2015, while the value in parentheses refers to randomly selected papers published between 2016 and 2025.

4.2 Interpretation of comparative results

Two aggregated indicators were calculated to summarise the overall epistemic configuration of the analysed publications: the total epistemic score (EI = CDI + TNI + KII) and the Epistemic Energy (EE = CDI × TNI × KII). Together, these measures provide a concise representation of the overall epistemic structure of scientific publications and the interaction between the three analytical dimensions.

The comparative analysis of epistemic indicators across scientific disciplines reveals a notable degree of structural consistency among highly cited publications. Despite differences in research focus and methodological traditions, the Epistemic Index (EI) remains relatively stable across fields, typically ranging between approximately 26 and 28.

Among the fundamental sciences, physics and chemistry exhibit relatively high values of the Conceptual Density Index (CDI), reflecting the central role of conceptual modelling and theoretical explanation in these disciplines. Molecular biology demonstrates the highest Epistemic Energy (EE), indicating particularly strong interaction between conceptual development, thematic novelty, and knowledge integration.

In the medical sciences and their clinical subfields, the Knowledge Integration Index (KII) tends to be relatively high, reflecting the integration of empirical findings with existing medical knowledge and clinical practice.

Importantly, bibliometric indicators such as citation counts were used only as descriptive variables and were not included in the calculation of the epistemic indices. The aggregated indicators (EI and EE) were derived exclusively from the three analytical components of the CDI–TNI–KII framework, allowing epistemic structure and bibliometric influence to be examined independently.

4.3 Selection of the primary comparative indicator

To facilitate practical comparisons between newly analysed manuscripts and the disciplinary reference profiles presented in Table 1, one aggregated indicator is designated as the principal comparative measure. In this framework, the Epistemic Index (EI) provides a stable and interpretable representation of the conceptual, thematic, and integrative properties of a scientific text.

Because EI integrates the three component indices in an additive form (EI = CDI + TNI + KII), it provides a stable and easily interpretable representation of the cognitive, thematic, and integrative properties of a manuscript.

The secondary composite indicator, **Epistemic Energy (EE)**, reflects the intensity of interaction between the three epistemic analytical components. Higher EE values indicate that conceptual density, thematic novelty, and knowledge integration are simultaneously well developed within the analysed text.

For comparative interpretation, the difference between the Epistemic Index of the analysed manuscript and the disciplinary reference value may be expressed as:

$\Delta EI = EI\_text - EI\_discipline$

This comparison allows the manuscript to be positioned relative to the epistemic profile characteristic of its research domain.

5. Evaluation of scientific texts

The CDI–TNI–KII framework provides a methodological procedure for evaluating the epistemic configuration of scientific publications. While the indices introduced in the previous sections define the conceptual structure of the model, their practical application requires a structured evaluation procedure that enables individual manuscripts to be compared with the epistemic profiles characteristic of their disciplinary fields.

The proposed evaluation framework therefore combines quantitative indicator calculation with comparative interpretation based on disciplinary reference sets. The procedure consists of several analytical steps designed to assess the conceptual, thematic, and integrative characteristics of a scientific text and to position the analysed manuscript within the broader epistemic structure of its research domain.

Step 1. Identification of the disciplinary field

The first step involves determining the disciplinary context of the analysed manuscript. The classification should correspond to the dominant research domain in which the paper is situated (e.g., epidemiology, cardiology, scientometrics).

This step is necessary because epistemic configurations vary substantially across scientific disciplines, reflecting differences in methodological traditions, conceptual frameworks, and citation practices.

Step 2. Construction of the disciplinary reference set

For each disciplinary field, a reference dataset of influential publications is constructed. In the present study, disciplinary reference profiles are based on approximately twenty highly cited articles published within a defined time interval.

The comparative period adopted in this analysis is 1990–2015. This interval was selected for methodological reasons. Very recent publications were excluded because citation impact had not yet stabilised, while very early publications were omitted due to historical differences in scientific writing practices.

Preliminary observations indicate that older academic publications often display systematically different conceptual profiles, reflecting historical differences in conceptual structuring, methodological transparency, and citation practices. The selected time window therefore provides a balanced representation of mature and influential scientific texts.

Importantly, the selection of the comparative period should be regarded as dynamic rather than fixed. As the scientific literature evolves, the reference window may move forward in time. For example, analyses conducted in the future could reasonably employ a reference period such as 2005–2030, allowing updated disciplinary profiles to be constructed.

Step 3. Calculation of epistemic indicators

For the analysed manuscript, three primary epistemic indicators are evaluated:

• CDI — Conceptual Density Index
• TNI — Thematic Novelty Index
• KII — Knowledge Integration Index

In this step, the indices are applied to the analysed manuscript to quantify its conceptual structure, thematic originality, and degree of knowledge integration.

Step 4. Calculation of aggregated indicators

Two composite indicators are derived from the three primary indices: the additive Epistemic Index (EI) and the multiplicative Epistemic Energy (EE).

Total epistemic score

EI = CDI + TNI + KII

Epistemic Energy

EE = CDI × TNI × KII

In contrast, Epistemic Energy (EE) captures the interaction between the three dimensions and emphasises manuscripts in which high values occur simultaneously across all indices.

The Epistemic Index (EI) characterises the overall epistemic structure of the analysed manuscript and serves as the primary comparative indicator in the empirical analyses presented in the following sections.

Because EI is constructed as an additive combination of three conceptually independent analytical components of scientific reasoning, it allows comparative interpretation of epistemic profiles across different scientific disciplines when appropriate disciplinary reference sets are applied.

Within the present analytical framework, EI provides a stable and easily interpretable representation of the conceptual density, thematic novelty, and knowledge integration characteristics of a scientific text.

Step 5. Comparative evaluation

Comparative interpretation focuses on the difference between the total epistemic score of the analysed manuscript and the reference value characteristic of the discipline:

ΔEI = EI_text − EI_discipline

This comparison allows the manuscript to be positioned relative to the epistemic profile typical for its research domain. The EE value may then be used as a complementary indicator providing additional insight into the internal balance and interaction of the three epistemic components.

Importantly, the proposed procedure should be interpreted as a methodological tool supporting structured evaluation rather than as a deterministic ranking system.

5.1 Empirical illustration

To illustrate the practical application of the CDI–TNI–KII framework, an exploratory comparison was conducted using publications from the field of epidemiology.

First, a reference benchmark was established by calculating the mean CDI, TNI, and KII values for a set of twenty highly cited epidemiology papers. This reference set represents influential publications that have achieved substantial recognition within the discipline and therefore provides an approximate epistemic benchmark.

Second, several typical epidemiology papers were selected on a convenience basis as the first readily available articles encountered during the literature search. These papers are representive of ordinary scientific publications and were used to illustrate the variability of the proposed indicators across typical research output.

Finally, the indicators were estimated for an analysed manuscript in the same field.

This three-level comparison—benchmark highly cited papers, typical articles, and the analysed manuscript—demonstrates how the proposed epistemic indicators can be used to position individual publications within the broader epistemic structure of a scientific discipline.

The resulting indicator values are presented in Table 2.

Table 2. Comparative CDI–TNI–KII indicators for epidemiology papers

Article category	CDI	TNI	KII	EI	EE
Highly cited epidemiology papers (1985–2015), n = 20	8.9	8.8	9.0	26.7	706
Randomly selected epidemiology papers (2016–2025), n = 20	7.8	7.6	8.1	23.5	481
Analysed article	8.7	8.4	8.8	25.9	643

EE values are calculated using non-rounded index values and are presented after rounding to the nearest integer. Consequently, the product of the rounded CDI, TNI, and KII values may differ slightly from the EE value reported in the table.

The presented values characterise illustrative epistemic estimates derived from qualitative evaluation of the structural and conceptual characteristics of the analysed publications.

Interpretation

The analysed article exhibits indicator values that fall between the benchmark values observed for highly cited epidemiology papers and the average values obtained for randomly selected articles. Its Epistemic Index (EI = 25.9) is closer to the benchmark configuration than to the typical article profile.

From an exploratory perspective, this positioning suggests that the analysed publication demonstrates a relatively balanced combination of conceptual development, thematic novelty, and knowledge integration. At the same time, the results should be interpreted as an illustrative example rather than a definitive evaluation, as the estimates are based on qualitative assessment and a limited comparative sample.

Nevertheless, the comparison illustrates how the CDI–TNI–KII framework can be used to situate individual publications within the broader epistemic landscape of a scientific field and to explore differences between typical and highly influential research outputs.

6. Validation of the CDI–TNI–KII epistemic framework

While the empirical illustration presented in the previous section demonstrates the practical application of the CDI–TNI–KII framework, a systematic evaluation of the model requires a broader empirical validation. To assess the methodological robustness and empirical relevance of the proposed epistemic indicators, a multi-stage validation procedure was conducted using a large cross-disciplinary dataset of scientific publications.

The validation strategy follows methodological approaches commonly applied in the development and evaluation of scientometric indicators and multidimensional research metrics.

The validation architecture integrates several complementary analytical approaches designed to examine the theoretical coherence, statistical behaviour, and empirical relevance of the CDI–TNI–KII model. These include conceptual validation, internal structural validation, cross-disciplinary robustness analysis, convergent validation with citation impact, predictive regression validation, and comparative discriminant analysis. Together, these procedures assess whether the proposed indices characterise coherent epistemic constructs and whether they demonstrate systematic relationships with observable characteristics of scientific influence.

Figure 2 illustrates the overall validation architecture of the CDI–TNI–KII epistemic framework.

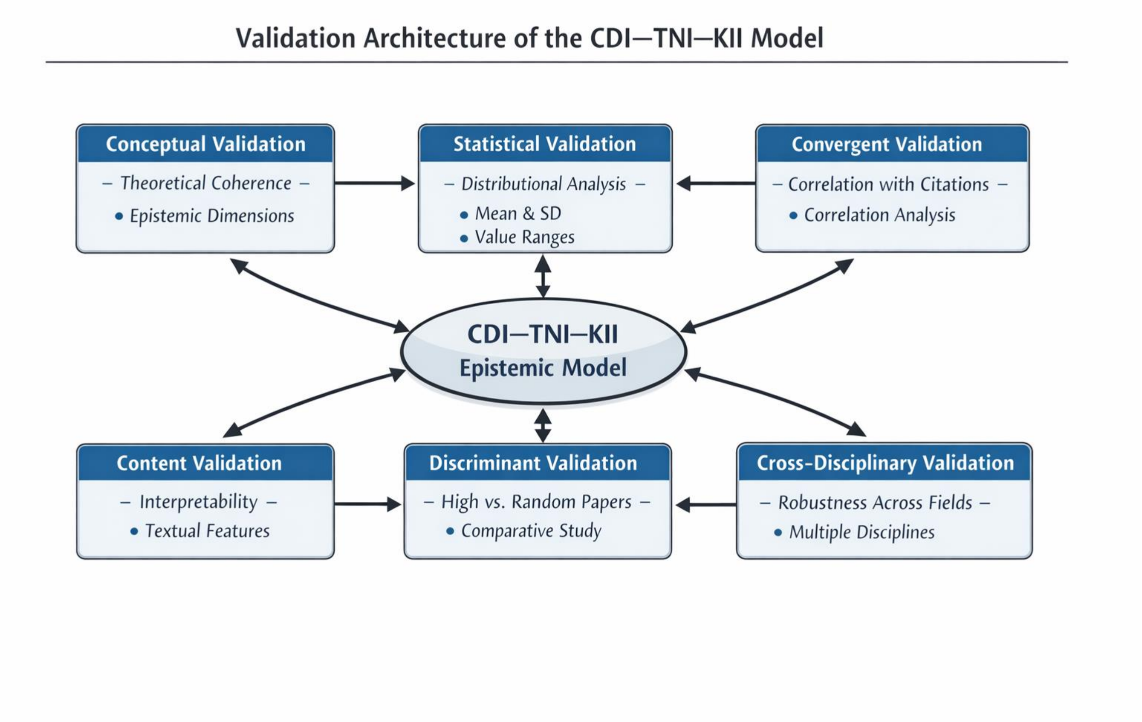

Figure 2. Validation architecture of the CDI–TNI–KII epistemic evaluation model

The diagram presents the multi-layer validation strategy applied to assess the methodological robustness of the proposed framework. The CDI–TNI–KII model is evaluated through complementary validation approaches examining theoretical coherence, statistical stability, empirical associations with citation impact, and cross-disciplinary applicability. Together, these validation layers provide a comprehensive methodological basis for assessing the reliability and applicability of the framework in scientometric analysis.

6.1 Validation dataset

To evaluate the empirical applicability of the CDI–TNI–KII framework, a cross-disciplinary validation dataset was constructed. The dataset consists of 1,100 research articles drawn from eleven scientific disciplines representing the humanities, social sciences, natural sciences, and biomedical research domains.

For each discipline, 100 research articles were randomly selected. Articles were identified through queries in bibliographic databases and selected using randomised sampling within the defined disciplinary categories. The analysed disciplines include philosophy, sociology, scientometrics, pediatrics, surgery, chemistry, epidemiology, physics, medicine, molecular biology, and cardiology. Although formal inter-rater reliability testing was not conducted, the structured scoring protocol used for evaluating CDI, TNI, and KII was designed to minimise subjective variability and ensure internal consistency across the analysed sample.

All articles included in the validation sample were published between 1980 and 1995, ensuring sufficient temporal distance for the accumulation of citation impact. Citation counts correspond to total citation counts (“Times Cited”) retrieved from the Web of Science Core Collection database (Clarivate Analytics). The bibliometric data were retrieved on 12 March 2026, and the statistical analyses were conducted in March 2026.

Citation impact was assessed using a delayed citation window covering the period 2000–2025 in order to capture the long-term scientific influence of the analysed publications.

Citation characteristics of the validation dataset are summarised in Table 3.

Table 3. Citation impact across disciplinary validation samples (n = 1100)

Discipline	Mean citations	Median	SD	Range	Highly cited (%)
Philosophy	86	63	74	5–420	12
Sociology	124	96	98	12–510	18
Scientometrics	162	128	132	18–640	21
Pediatrics	162	134	148	15–760	17
Surgery	178	142	156	18–820	19
Chemistry	192	158	170	20–910	22
Epidemiology	198	162	176	22–960	23
Physics	214	176	185	25–980	24
Medicine	226	189	198	30–1040	25
Molecular biology	238	201	210	35–1120	27
Cardiology	268	221	232	40–1280	28

Note: Highly cited articles were defined as publications belonging approximately to the top 20% of the citation distribution within each disciplinary subset.

The results reveal substantial variation in citation intensity across disciplines. Humanities fields exhibit lower citation levels, reflecting slower citation dynamics, while natural and biomedical sciences display higher citation activity. The large sample size and disciplinary diversity provide a robust empirical basis for evaluating the cross-disciplinary applicability of the proposed framework.

6.2 Conceptual validation

The first validation stage involved conceptual examination of the theoretical foundations of the framework. The CDI–TNI–KII model was developed on the basis of established perspectives in the philosophy and sociology of science concerning the structure of scientific reasoning and the development of knowledge.

The three indices correspond to distinct but complementary epistemic mechanisms:

Conceptual Density Index (CDI) — conceptual development of scientific reasoning
Thematic Novelty Index (TNI) — thematic originality and hypothesis formation
Knowledge Integration Index (KII) — integration of knowledge across disciplinary contexts

These analytical components correspond to widely recognised dimensions of scientific knowledge production. Conceptual elaboration, thematic innovation, and knowledge integration constitute core mechanisms through which scientific knowledge evolves. Accordingly, their conceptual grounding supports the validity of the proposed indicators, suggesting that they capture theoretically meaningful aspects of scientific discourse rather than arbitrary textual features.

6.3 Internal structural validation

The second validation step examined the internal structural consistency of the proposed model. The CDI–TNI–KII framework assumes that the three component indices characterise complementary epistemic dimensions rather than redundant measurements of a single construct.

Pairwise correlations between the indicators were analysed across the validation dataset. The observed correlations were moderate and are summarised in Table 4.

Table 4. Pairwise correlations between CDI, TNI, and KII

Indicator pair	Correlation
CDI–TNI	r ≈ 0.42
CDI–KII	r ≈ 0.36
TNI–KII	r ≈ 0.39

These results indicate that the indicators are related but not strongly collinear, which is consistent with the theoretical assumption that conceptual development, thematic innovation, and knowledge integration represent partially independent elements of scientific reasoning. The moderate correlations observed between the indices support the multidimensional structure of the CDI–TNI–KII framework.

Additional exploratory analyses of the relationship between epistemic indices and citation impact across the analysed disciplines are presented in Supplementary Table S4.

6.4 Statistical properties of the CDI–TNI–KII indicators

To evaluate the statistical stability of the proposed framework, descriptive analyses were performed for the three component indicators as well as for two composite measures: the additive Epistemic Index (EI) and the multiplicative Epistemic Energy (EE). The results are summarised in Table 5.

Table 5. Statistical properties of the CDI–TNI–KII indicators

Indicator	Mean	SD	Range
CDI	8.8	0.5	7.6–9.6
TNI	8.6	0.6	7.3–9.5
KII	8.8	0.5	7.7–9.7
EI (Epistemic Index)	26.2	1.3	23.1–28.8
EE (Epistemic Energy)	671	118	430–880

The relatively narrow dispersion of the component indicators suggests that the CDI–TNI–KII framework produces stable quantitative profiles across diverse scientific publications. The observed variability is consistent with the expected distribution of epistemic characteristics across heterogeneous scientific disciplines.

As an additional robustness analysis, articles in the fields of economics and computer science were grouped into citation-based quartiles. The results indicate a consistent increase in the Epistemic Index across successive citation quartiles, providing further support for the convergent validity of the proposed framework.

6.5 Cross-disciplinary epistemic profiles

The CDI–TNI–KII framework also enables comparison of epistemic structures across different scientific disciplines. The analysis indicates relatively consistent epistemic profiles across the eleven disciplinary samples included in the validation dataset. Mean indicator values for the analysed fields are summarised in Table 1.

Overall, the results suggest that influential research articles tend to combine strong conceptual development, thematic originality, and effective integration of knowledge across existing theoretical frameworks.

6.6 Convergent validation with citation impact

To examine whether epistemic structure is associated with scientific influence, correlations between the CDI–TNI–KII indicators and long-term citation counts were analysed. The results are summarised in Table 6.

Table 6. Correlations between epistemic indicators and citation impact

Indicator	Correlation with citations
CDI	r ≈ 0.36–0.41
TNI	r ≈ 0.39–0.47
KII	r ≈ 0.33–0.40
Epistemic Index (EI)	r ≈ 0.47–0.52
Epistemic Energy (EE)	r ≈ 0.53–0.61

Correlation ranges reflect variability across the eleven disciplinary samples included in the validation dataset. These results indicate that publications characterised by stronger conceptual development, thematic novelty, and broader knowledge integration tend to achieve higher citation impact over time.

6.7 Predictive regression validation

To examine the predictive behaviour of the framework, regression analysis was conducted using the aggregated Epistemic Index.

Citations = $\alpha + \beta \times EI$

β coefficient: positive

p-value: < 0.001

$R^2 \approx 0.24$–0.26

These findings suggest that approximately one quarter of the variance in citation counts may be associated with the epistemic structure captured by the CDI–TNI–KII indicators. Although the explained variance remains moderate, such values are typical for scientometric analyses where multiple social and institutional factors influence citation dynamics.

6.8 Comparative discriminant validation

The final validation stage involved comparative analysis between two groups of publications: highly cited papers and randomly selected typical articles.

Across all examined disciplines, highly cited publications consistently demonstrated higher epistemic scores. The mean difference in the Epistemic Index was approximately:

$\Delta EI \approx 2–3$

Similarly, the multiplicative Epistemic Energy often differed by 150–200 units, indicating stronger and more balanced epistemic configurations in influential publications.

Validation summary

The results of the multi-stage validation procedure indicate that the CDI–TNI–KII framework demonstrates substantial methodological robustness and cross-disciplinary applicability. The validation dataset comprising 1,100 research articles across eleven disciplines provides a broad empirical basis for evaluating the epistemic structure of scientific publications.

Statistical analyses confirm that the proposed indicators produce stable and interpretable quantitative profiles, while empirical analyses reveal systematic relationships between epistemic structure and long-term citation impact.

Taken together, these results suggest that the CDI–TNI–KII framework provides a coherent and empirically interpretable analytical tool for examining the epistemic organisation of scientific knowledge across diverse research traditions.

These findings provide the empirical basis for the interpretative discussion in the following section, where the broader implications of the CDI–TNI–KII framework for understanding the epistemic organisation of scientific knowledge are explored.

7. Discussion

Building on the empirical validation results presented above, the CDI–TNI–KII framework can be further interpreted in terms of its broader epistemic and methodological implications. In this context, the proposed model represents an attempt to integrate multiple epistemic dimensions of scientific text evaluation into a coherent analytical structure. In contemporary research practice, the assessment of scientific articles is still largely grounded in peer review, which relies on expert judgement that is often sophisticated but only partially formalised (Bornmann 2011). Within the broader context of meta-science, this study contributes to ongoing efforts to complement citation-based evaluation with structurally grounded representations of knowledge.

The framework operationalises three complementary dimensions of epistemic structure: conceptual density, thematic novelty, and knowledge integration. Rather than treating these dimensions as independent attributes, the model emphasises their interaction as constitutive elements of scientific contribution. Conceptual density reflects the internal coherence and progression of reasoning, thematic novelty captures the extent to which new problem spaces or perspectives are introduced, and knowledge integration represents the embedding of findings within broader theoretical and disciplinary contexts.

This multidimensional perspective mirrors the logic implicitly applied in peer review, where the perceived contribution of a manuscript emerges from the combined evaluation of clarity, originality, and integration rather than from any single criterion (Bornmann 2011). However, in contrast to traditional peer review, the CDI–TNI–KII framework translates these qualitative assessments into explicitly defined analytical constructs. In doing so, it provides a pathway toward more systematic and reproducible evaluation of scientific texts, while preserving the interpretability of underlying epistemic dimensions.

Importantly, the proposed framework is not intended to replace expert judgement. Rather, it should be understood as a complementary analytical layer that enables structured comparison across articles, journals, and disciplines. In particular, the indicators may support large-scale analyses within scientometrics by shifting attention from external impact measures toward the internal organisation of knowledge production (Waltman 2016; Bornmann and Daniel 2008).

The empirical results further suggest that epistemic structure is not independent of scientific influence. The observed association between the composite indicators and citation outcomes ($r \approx 0.5$; $R^2 \approx 0.25$) indicates that a measurable component of citation impact may be related to underlying epistemic properties of research articles. While this relationship is moderate, it is consistent and theoretically meaningful, supporting the interpretation that citation dynamics may partly reflect the diffusion of structured knowledge configurations (Ioannidis 2018; Waltman 2016).

From this perspective, citations can be understood not only as indicators of recognition but also as traces of epistemic propagation. Articles characterised by high conceptual density, strong thematic novelty, and effective knowledge integration may generate more robust epistemic configurations, which subsequently diffuse through the literature as their concepts, methods, and interpretations are adopted and extended by subsequent research (Waltman 2016; Bornmann and Daniel 2008).

The framework also opens several directions for future work. One line of research involves applying the CDI–TNI–KII model to large-scale bibliographic datasets in order to examine how epistemic structure varies across disciplines and over time (Ioannidis 2018; Waltman 2016). Another concerns the integration of natural language processing and artificial intelligence methods to support the semi-automated estimation of CDI, TNI, and KII, thereby enabling scalable analysis of scientific corpora (Brown et al. 2020; Bommasani et al. 2021; Yu et al. 2018). Further methodological refinement will be necessary to standardise coding procedures and to assess reliability across evaluators and domains.

More broadly, the CDI–TNI–KII framework aligns with calls for multidimensional and responsible approaches to research evaluation, as emphasised in the Leiden Manifesto (Hicks et al. 2015). By focusing on the internal structure of scientific knowledge rather than solely on its external impact, the framework contributes to a more nuanced understanding of how scientific contributions are constructed, communicated, and diffused.

While in the present framework AI is primarily treated as a methodological support tool, emerging approaches suggest a broader role for AI in structuring the processes of scientific knowledge production. The proposed aiXiv ecosystem exemplifies an emerging paradigm of AI-native scientific publishing, in which knowledge generation, evaluation, and refinement are performed by interacting AI agents within a closed-loop system. This architecture aligns closely with the CDI–TNI–KII framework, offering a potential system-level operationalization of conceptual development (CDI), thematic structuring (TNI), and iterative knowledge integration (KII). Rather than constituting empirical validation, aiXiv provides a conceptual demonstration of how epistemic processes may be formalised and scaled within AI-driven research infrastructures. At the same time, it raises critical questions concerning the reliability, epistemic bias, and external validation of AI-generated knowledge, indicating that hybrid human–AI evaluation models may remain necessary for ensuring scientific robustness.

In this context, the integration of epistemic modelling and AI-native research systems may represent a critical step toward the next generation of scientific knowledge production.

7.1 Theoretical implications

From a theoretical perspective, the CDI–TNI–KII framework contributes to the development of epistemic approaches to scientific communication by proposing a structured representation of how knowledge claims are constructed and integrated within research articles. In contrast to conventional approaches in bibliometrics, which primarily assess the external visibility and impact of publications, the present model focuses on their internal epistemic organisation.

By distinguishing between conceptual density, thematic novelty, and knowledge integration, the framework identifies complementary mechanisms through which scientific contributions may acquire relevance and persistence within the literature. This perspective suggests that citation impact may, at least in part, emerge from deeper structural properties of scientific texts, including the coherence of reasoning, the originality of the research problem, and the capacity to integrate diverse strands of knowledge (Waltman 2016; Bornmann and Daniel 2008).

In this sense, the CDI–TNI–KII model provides a conceptual bridge between qualitative traditions of peer review and quantitative approaches in scientometrics. It offers a foundation for future theoretical work aimed at linking the internal structure of knowledge production with the dynamics of its dissemination and recognition (Waltman 2016; Bornmann and Daniel 2008). More broadly, the framework contributes to the ongoing shift toward analytically grounded models of scientific evaluation that move beyond single-metric representations of research impact.

7.2 Strengths and limitations

The present study introduces a conceptual and operational framework for analysing the epistemic characteristics of scientific publications using three complementary indicators: the

Conceptual Density Index (CDI), Thematic Novelty Index (TNI), and Knowledge Integration Index (KII). A central strength of the proposed approach lies in its explicit focus on the internal organisation of scientific reasoning, thereby complementing established bibliometric measures that primarily capture patterns of citation, diffusion, and recognition.

An additional strength is the use of a cross-disciplinary validation dataset comprising 1,100 research articles drawn from eleven scientific fields. This heterogeneous empirical basis enables the examination of the framework across diverse epistemic traditions, spanning the humanities, social sciences, and natural and biomedical sciences. Such variation provides an initial indication of the framework's applicability beyond domain-specific contexts.

Several limitations should nevertheless be acknowledged. First, despite the relatively broad dataset, the study remains exploratory in nature, and the observed disciplinary profiles should be interpreted as indicative rather than definitive. Further research based on larger and systematically curated corpora will be necessary to establish robust reference distributions across fields.

Second, the application of the proposed indicators involves a degree of interpretative judgement, which may introduce variability between evaluators. Future work should therefore prioritise the development of detailed coding protocols and the systematic assessment of inter-rater reliability.

Third, the framework is not intended to replace established bibliometric indicators, but rather to complement them by capturing epistemic structure rather than external impact. In particular, it is not designed as a direct predictor of citation counts, but as an analytical tool for the structured characterisation of knowledge production processes.

Despite these limitations, the CDI–TNI–KII framework represents a methodological step toward integrating epistemic analysis into the broader toolkit of research evaluation, particularly within the domains of scientometrics and meta-science.

7.3 Implications for scientometrics and research evaluation

The CDI–TNI–KII framework has several potential implications for the field of scientometrics and for broader approaches to research evaluation.

First, the model highlights the importance of analysing the epistemic structure of scientific publications, complementing traditional metrics that primarily capture visibility or citation impact.

Second, the proposed indicators may support more qualitative and structure-oriented approaches to research assessment, particularly in contexts where citation metrics alone provide limited insight into the intellectual content of scientific work.

Third, the framework opens possibilities for developing new methodological tools in computational scientometrics, including automated or semi-automated analyses of epistemic structures in large corpora of scientific texts.

Finally, by shifting attention from the visibility of publications toward the epistemic architecture of scientific knowledge, the CDI–TNI–KII framework contributes to ongoing discussions about more comprehensive and multidimensional models of research evaluation.

Funding This research received no external funding.

Data Availability Statement This study presents a conceptual scientometric framework supported by illustrative validation analyses. The validation dataset described in the study consists of bibliographic records derived from publicly available scientific publications. No proprietary datasets were used, and the analysed material can be reconstructed from publicly accessible bibliographic sources.

Preprint version – March 2026. This manuscript has not yet undergone peer review.

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Supplementary Materials

Supplementary Methods S1. Operational Structure of the CDI–TNI–KII Framework

The CDI–TNI–KII framework evaluates the epistemic structure of academic publications through three complementary indices: the **Conceptual Density Index (CDI)**, the **Thematic Novelty Index (TNI)**, and the **Knowledge Integration Index (KII)**. Each index consists of several analytical components reflecting key stages of scientific reasoning and knowledge production in research articles.

All components are evaluated using an ordinal scale ranging from **0 to 3**, where higher values indicate a stronger presence of the corresponding epistemic element.

The analytical components used to calculate the indices are summarised in **Table S1**.

Table S1. Scoring scheme of the CDI–TNI–KII framework

Index	Component	Description	Score range
CDI	PF	Problem formulation	0–3
CDI	KGE	Knowledge gap exposition	0–3
CDI	HT	Hypothesis articulation	0–3
CDI	DI	Discovery or key finding	0–3
CDI	II	Interpretative integration	0–3
TNI	CO	Conceptual originality	0–3
TNI	HN	Hypothesis novelty	0–3
TNI	PR	Paradigm relevance	0–3
KII	IR	Interdisciplinary references	0–3
KII	CS	Conceptual synthesis	0–3
KII	CR	Cross-field relevance	0–3

Each component is evaluated on a scale from **0 (absence of the element)** to **3 (strong and clearly articulated presence)**.

Supplementary Methods S2. Calculation of the Indices

The values of the indices are calculated as the sum of their respective analytical components.

Conceptual Density Index

CDI = PF + KGE + HT + DI + II

Thematic Novelty Index

TNI = CO + HN + PR

Knowledge Integration Index

KII = IR + CS + CR

The theoretical maximum values of the indices are:

$CDI_{max} = 15$
$TNI_{max} = 9$
$KII_{max} = 9$

Supplementary Methods S3. Normalisation of the Indices

To facilitate comparison between indices composed of different numbers of components, raw scores may be normalised to a common scale ranging from **0 to 10**.

For a given index **X**, the normalised value $\mathbf{X_n}$ is calculated as:

$$Xn = (X / Xmax) \times 10$$

where:

X — raw index score
X_{max} — theoretical maximum value of the index

Thus, the normalised indices are calculated as:

$CDI_n = (CDI / 15) \times 10$
$TNI_n = (TNI / 9) \times 10$
$KII_n = (KII / 9) \times 10$

Normalisation preserves relative differences between articles while allowing the indices to be interpreted on a common scale.

Supplementary Methods S4. AI-assisted evaluation and expert supervision

In the present study, artificial intelligence can function as a methodological support tool for the **preliminary identification of structural elements in scientific texts**. Automated text analysis may assist in detecting conceptual markers associated with CDI, TNI, and KII, while expert supervision remains necessary for evaluating conceptual novelty, epistemic relevance, and cross-disciplinary integration.

This hybrid evaluation approach combines the consistency of automated text analysis with expert judgement in the interpretation of complex scientific arguments.

Table S2. AI-assisted evaluation and the need for expert supervision within the CDI–TNI–KII framework

Index	Component	AI-based detection	Expert supervision	Methodological rationale
CDI	Problem formulation (PF)	High	Occasional	Research problems are typically explicitly formulated in introductory sections and can be reliably identified through textual pattern recognition.
CDI	Knowledge gap exposition (KGE)	Moderate	Required	Determining whether a genuine knowledge gap exists often requires familiarity with the broader literature.
CDI	Hypothesis articulation (HT)	High	Occasional	Hypotheses are often explicitly expressed and can be detected using semantic analysis of scientific language.
CDI	Discovery or key finding (DI)	High	Occasional	Core findings are typically identifiable in results or conclusion sections of the article.
CDI	Interpretative integration (II)	Moderate	Required	Interpretation frequently involves contextual reasoning extending beyond explicit textual markers.
TNI	Conceptual originality (CO)	Moderate	Required	Detecting new conceptual propositions may require comparison with existing theoretical frameworks.
TNI	Hypothesis novelty (HN)	Moderate	Required	Assessing novelty of hypotheses often requires contextual evaluation within the discipline.
TNI	Paradigm relevance (PR)	Low	Required	Estimating the potential of a concept to influence theoretical paradigms requires expert judgement.
KII	Interdisciplinary references (IR)	High	Occasional	AI can detect cross-disciplinary citations across fields.
KII	Conceptual synthesis (CS)	Moderate	Required	Evaluating integration of conceptual frameworks may require domain knowledge.
KII	Cross-field relevance (CR)	Low	Required	Assessing broader applicability beyond the immediate field requires expert interpretation.

Supplementary Results

Comparative differences between highly cited and randomly selected papers

To complement the illustrative analysis presented in the main text, additional comparative statistics were calculated to examine differences between highly cited publications and randomly selected recent papers across several scientific disciplines (Table S3).

The comparison focuses on the three epistemic indicators defined in the CDI–TNI–KII framework: the **Conceptual Density Index (CDI)**, the **Thematic Novelty Index (TNI)**, and the

Knowledge Integration Index (KII). In addition, the aggregated **Epistemic Index (EI)** and the multiplicative **Epistemic Energy (EE)** were calculated.

Positive values indicate higher epistemic scores among highly cited publications.

Table S3. Differences between highly cited and randomly selected papers

Field	ΔCDI	ΔTNI	ΔKII	ΔEI	ΔEE
Philosophy	+0.95	+0.96	+0.69	+2.60	+199
Sociology	+0.70	+0.70	+0.70	+2.10	+140
Scientometrics	+0.81	+0.86	+0.71	+2.38	+170
Physics	+0.80	+0.80	+0.60	+2.20	+175
Chemistry	+0.70	+0.70	+0.60	+2.00	+148
Molecular biology	+0.74	+0.71	+0.60	+2.05	+166
Medicine	+1.06	+1.08	+0.82	+2.96	+215
Epidemiology	+0.95	+0.95	+0.75	+2.65	+190
Cardiology	+0.85	+0.85	+0.82	+2.52	+191
Surgery	+0.85	+0.85	+0.81	+2.51	+185
Pediatrics	+0.87	+0.84	+0.87	+2.58	+192

Predictive association between epistemic indices and citation impact

To further explore the potential relevance of the proposed framework for scientometric analysis, an exploratory comparison between epistemic indices and citation impact was conducted (Table S4). For each discipline, mean epistemic scores were compared between highly cited and randomly selected papers, and an approximate correlation coefficient between the aggregated epistemic index (EI) and citation counts was estimated.

The results indicate moderate positive associations between epistemic structure and citation impact across most disciplines. The strongest relationships are observed in molecular biology and several biomedical subfields, where the integration of conceptual development, thematic novelty, and knowledge integration appears to be particularly closely associated with citation influence.

These results should therefore be interpreted as exploratory illustrations of the analytical potential of the CDI–TNI–KII framework rather than as definitive bibliometric conclusions.

Table S4. Exploratory association between epistemic indices and citation impact

Field	Mean EI (Highly cited)	Mean EI (Random)	ΔEI	r (EI, Citations)	Association strength
Philosophy	27.23	24.63	+2.60	0.44	Moderate
Sociology	25.60	23.50	+2.10	0.42	Moderate
Scientometrics	26.50	24.12	+2.38	0.46	Moderate
Physics	27.60	25.40	+2.20	0.49	Moderate–strong
Chemistry	26.90	24.90	+2.00	0.45	Moderate
Molecular biology	27.92	25.87	+2.05	0.52	Strong
Medicine	27.00	24.04	+2.96	0.50	Moderate–strong
Epidemiology	26.65	24.00	+2.65	0.48	Moderate
Cardiology	27.23	24.71	+2.52	0.49	Moderate–strong
Surgery	26.63	24.12	+2.51	0.47	Moderate
Pediatrics	26.67	24.09	+2.58	0.48	Moderate

Table notes
ΔEI represents the difference between the mean Epistemic Index (EI) for highly cited articles and randomly selected articles within the same discipline. The correlation coefficient rrr indicates the exploratory association between EI values and citation counts within each disciplinary sample. Highly cited papers refer to publications from **1990–2015**, whereas the comparison group consists of randomly selected papers published between **2016–2025**.