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Interdisciplinarity Beyond Diversity: A Multidimensional Framework for Measuring Conceptual Integration in Scientific Research

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Abstract

This study examines the relationship between conceptual integration and reference-based diversity in the measurement of interdisciplinarity. Using a corpus of 112 scientific articles, we operationalize conceptual integration through a concept-level indicator (IIC) based on alignment density and structural synthesis and compare it with Rao–Stirling diversity derived from reference distributions.

The results show a near-zero correlation between integration and diversity (Spearman $\rho = 0.041$), indicating that these dimensions capture fundamentally different aspects of interdisciplinarity. While diversity reflects the spread of disciplinary sources, it does not account for their conceptual articulation. In contrast, conceptual integration captures the extent to which knowledge is semantically aligned and synthesized.

A quadrant-based analysis reveals distinct regimes, including fragmented interdisciplinarity (high diversity, low integration) and focused integration (low diversity, high integration), demonstrating that disciplinary breadth is neither a necessary nor a sufficient condition for integration.

To address this limitation, we introduce a composite indicator (IC-IDR) that combines integration, diversity, and coherence. The results show that high interdisciplinarity emerges from the interaction between these dimensions rather than from diversity alone.

These findings challenge the dominant reliance on diversity-based metrics and support a reconceptualization of interdisciplinarity as a multidimensional and integration-centered phenomenon. The proposed framework provides a more discriminative and theoretically grounded approach for evaluating interdisciplinary research.

Keywords

Interdisciplinarity, Conceptual integration, Rao–Stirling diversity, Scientometrics, Knowledge integration, Research evaluation.

1. Introduction

The measurement of interdisciplinarity remains a central challenge in scientometric research. Despite significant advances, most existing approaches rely on diversity-based indicators, implicitly if the distribution of disciplinary categories reflects the degree of knowledge integration. However, this assumption remains insufficiently tested at the conceptual level.

Over the past decades, interdisciplinarity has been predominantly operationalized through indicators that quantify the distribution of disciplinary references. Among these, the Rao–Stirling diversity has become one of the most widely adopted measures, capturing interdisciplinarity in terms of variety, balance, and disparity (Stirling, 2007; Porter & Rafols, 2009). While these metrics provide valuable insights into the compositional structure of research, they do not account for how disciplines are conceptually connected within the internal organization of knowledge.

Existing measures of interdisciplinarity have been widely questioned in terms of consistency and validity (Wang & Schneider, 2018; Leydesdorff et al., 2019), particularly those based on diversity indicators such as Rao–Stirling (Nakhoda et al., 2023), which are extensively used in comparative analyses of research systems (Cassi et al., 2017).

This limitation becomes particularly relevant in contexts where interdisciplinarity is associated with knowledge synthesis and problem-solving across domains. In such cases, the critical issue is not only how many disciplines are involved, but how they interact, align, and contribute to the construction of new knowledge. The distinction between multidisciplinarity (as the coexistence of multiple disciplines) and interdisciplinarity (as their effective integration) thus becomes fundamental yet remains insufficiently captured by existing quantitative approaches.

A relevant conceptual foundation for addressing this gap can be found in the model proposed by Melgarejo and Cadena, which conceptualizes interdisciplinarity as a process of conceptual alignment and transformation across disciplinary ontologies (Melgarejo Heredia & Cadena Vinueza, 2015). In this framework, interdisciplinarity is not defined by the mere interaction of disciplinary domains, but by observable changes in the ontology of concepts as they evolve through collaborative processes. Interdisciplinary knowledge emerges when concepts are redefined, aligned, or merged, generating new shared meanings across disciplinary boundaries.

This perspective introduces a structural and semantic understanding of interdisciplinarity, emphasizing the internal organization of knowledge rather than its external composition. However, while the Melgarejo–Cadena model provides a robust theoretical and methodological basis, it does not offer a scalar metric suitable for large-scale quantitative analysis across scientific corpora. As a result, integration-based perspectives remain difficult to operationalize in scientometric studies.

In response, this study proposes a concept-level operationalization of integration, focusing on the semantic alignment and structural synthesis of knowledge components.

In this paper, we introduce the **Interdisciplinary Integration Coefficient (IIC)**, a novel metric designed to operationalize conceptual integration as a measurable dimension of interdisciplinarity. The IIC builds directly upon the principles of the Melgarejo–Cadena model by quantifying the extent to which disciplines are connected through aligned conceptual pairs. Rather than relying on reference diversity, the IIC captures the internal structure of knowledge by identifying and measuring conceptual bridges between disciplines.

The proposed approach is applied to a corpus of interdisciplinary articles affiliated with Latin American institutions. The methodology combines conceptual pair extraction, the construction of disciplinary interaction networks, and a comparative analysis with both simplified and full Rao–Stirling indices derived from Scopus and SCImago classifications. This design enables a direct empirical test of whether diversity-based indicators adequately reflect conceptual integration.

The results demonstrate that conceptual integration is empirically independent from disciplinary diversity. Specifically, near-zero correlations are observed between the IIC and Rao–Stirling indices, indicating that diversity-based measures do not capture the integrative structure of interdisciplinary research. Furthermore, diversity-based indicators exhibit saturation effects that limit their discriminative capacity.

These findings challenge the dominant assumption underlying diversity-based approaches and suggest that interdisciplinarity cannot be inferred from disciplinary composition alone.

Based on these results, this study proposes a three-dimensional framework for the analysis of interdisciplinarity, comprising: (i) diversity, which captures the distribution of disciplines; (ii) interaction, which reflects their structural connections; and (iii)

integration, which measures conceptual synthesis. Within this framework, the IIC provides a critical missing dimension, enabling a more precise and differentiated understanding of interdisciplinary research.

Unlike prior studies that assume a positive relationship between diversity and interdisciplinarity, this study provides empirical evidence of their independence. These findings suggest that interdisciplinarity cannot be inferred from disciplinary composition alone, highlighting the need for integration-sensitive indicators.

The remainder of the paper is structured as follows. Section 2 reviews the theoretical background, contrasting diversity-based approaches with integration-based perspectives and introducing the Melgarejo–Cadena model as a conceptual foundation. Section 3 describes the methodology, including data collection, processing, and the formal definition of the IIC. Section 4 presents the results, focusing on the distribution of integration, the structure of disciplinary networks, and the comparison with Rao–Stirling indicators. Section 5 discusses the implications of the findings, and Section 6 concludes the paper.

2. Theoretical Background

2.1. Interdisciplinarity as diversity: dominant approaches

Interdisciplinarity has been extensively studied within scientometrics through quantitative indicators that characterize the disciplinary composition of scientific outputs. The dominant paradigm conceptualizes interdisciplinarity as a function of diversity, typically operationalized through three components: variety (the number of disciplines involved), balance (the distribution of contributions across disciplines), and disparity (the cognitive distance between them) (Stirling, 2007).

Among the most influential formulations, the Rao–Stirling diversity has emerged as a standard measure for assessing interdisciplinary diversity. This index integrates these three components into a single metric by combining the proportional representation of disciplines with a distance matrix reflecting their cognitive dissimilarity (Rao, 1982; Stirling, 2007). Its widespread adoption is due to its capacity to capture not only how many disciplines are present, but also how different they are from one another.

Diversity-based approaches have enabled large-scale analyses of scientific production, facilitating comparisons across institutions, disciplines, and regions. In particular, the incorporation of disparity has been considered a significant advancement, as it allows interdisciplinarity to be associated with cognitive distance and potential innovation (Porter & Rafols, 2009).

However, despite these advantages, diversity-based indicators are fundamentally compositional. They describe the distribution of disciplinary elements within a set of references or classifications, but do not account for how these elements are internally connected within the knowledge structure of a scientific work. In this sense, diversity

measures capture what is present, but not how it is integrated (Leydesdorff & Rafols, 2011).

This limitation introduces a critical assumption underlying the dominant paradigm: that disciplinary diversity reflects conceptual integration. This assumption, however, remains largely untested at the conceptual level and may not hold in practice. Scientific works may involve multiple disciplines without establishing meaningful conceptual connections between them, resulting in configurations that are diverse but not integrated.

Furthermore, when disparity is derived from predefined classification systems (such as journal categories), diversity measures may become sensitive to the structure of the classification itself. This can lead to situations in which interdisciplinarity scores reflect imposed taxonomic distances rather than the actual internal organization of knowledge.

These limitations suggest that diversity-based indicators, while informative, provide only a partial representation of interdisciplinarity. They are insufficient to distinguish between multidisciplinarity (the coexistence of disciplines) and interdisciplinarity understood as conceptual integration.

This gap motivates the need for alternative approaches that move beyond compositional diversity and focus on the structural and conceptual relationships between disciplines.

2.2. Interdisciplinarity as integration: a conceptual perspective

An alternative perspective conceptualizes interdisciplinarity not as a property of distribution, but as a process of integration. In this view, the defining characteristic of interdisciplinary research is not the coexistence of multiple disciplines, but the extent to which their knowledge structures are combined to produce new, coherent understandings.

This distinction has been widely discussed in interdisciplinary studies, where a clear differentiation is made between multidisciplinarity and interdisciplinarity. Multidisciplinarity refers to the juxtaposition of disciplinary perspectives without modifying their internal structures, whereas interdisciplinarity involves the integration of concepts, methods, or theories, leading to the transformation of the contributing disciplines (Klein, 2010; Repko & Szostak, 2020).

From this perspective, interdisciplinarity is inherently relational and process-oriented. It involves the alignment, negotiation, and synthesis of conceptual frameworks across disciplinary boundaries. Integration occurs when previously distinct conceptual systems are connected in ways that generate new meanings, relationships, or explanatory structures.

Importantly, integration requires more than interaction or collaboration. It entails conceptual coherence, where disciplinary contributions are reorganized into a unified

framework rather than merely aggregated. This process may involve the reinterpretation of concepts, the development of shared vocabularies, or the creation of hybrid constructs that cannot be reduced to a single disciplinary origin.

However, despite its conceptual clarity, this perspective faces a major limitation: the lack of scalable quantitative metrics. While diversity can be measured through observable distributions, integration depends on internal semantic relationships that are not directly captured by standard bibliometric data.

As a result, most large-scale scientometric studies continue to rely on diversity-based indicators, even when acknowledging their limitations. The absence of operational measures for integration has constrained empirical validation of integration-based theories.

This limitation highlights the need for approaches capable of bridging the gap between conceptual definitions of interdisciplinarity and their quantitative measurement.

2.3. The Melgarejo–Cadena model of conceptual integration

A relevant conceptual foundation for addressing this gap can be found in the model proposed by Melgarejo & Cadena, which conceptualizes interdisciplinarity as a process of conceptual alignment and transformation across disciplinary ontologies (Melgarejo Heredia & Cadena Vinueza, 2015).

In this framework, disciplines are understood as structured systems of concepts supported by distinct ontologies. Interdisciplinarity emerges when these ontologies interact, enabling the identification of correspondences, equivalences, and transformations between concepts originating in different domains.

The central mechanism of this process is conceptual alignment, which involves the mapping and reconciliation of concepts across disciplinary boundaries. This alignment is not merely associative, but transformative: concepts may be redefined, merged, or reorganized, leading to the emergence of shared meanings that transcend individual disciplines.

This model provides a rare formalization of interdisciplinarity as a process of conceptual transformation, offering a strong theoretical foundation for its quantitative operationalization. It shifts the focus from disciplinary composition to the internal structure of knowledge, emphasizing observable changes in conceptual organization.

However, despite its conceptual and methodological strengths, the model presents a key limitation for large-scale scientometric analysis. While it enables the identification and description of conceptual alignment (particularly through ontology mapping), it does not provide a scalar metric that allows systematic comparison across large corpora.

This limitation is critical in contexts where hundreds or thousands of publications must be analyzed. Without a quantitative indicator, integration remains difficult to measure, compare, and incorporate into existing evaluation frameworks.

The present study builds directly upon this model by translating its core principles into a measurable indicator, enabling the empirical analysis of conceptual integration at scale.

2.4. Structural interdisciplinarity: toward a measurable definition

The perspectives discussed above reveal a fundamental distinction in the study of interdisciplinarity. Diversity-based approaches conceptualize interdisciplinarity as a property of distribution, whereas integration-based perspectives emphasize it as a process of conceptual transformation.

Bridging these perspectives requires a framework that captures the internal structure of knowledge integration. In this context, we introduce the concept of structural interdisciplinarity, defined as the extent to which disciplines are connected through coherent conceptual relationships within a scientific work.

Structural interdisciplinarity differs from diversity in that it does not depend on the number or distance of disciplines, but on the presence and strength of conceptual linkages that integrate their contributions. These linkages can be understood as observable connections between concepts originating in different disciplinary domains, reflecting processes of alignment, transformation, and synthesis.

From this perspective, interdisciplinarity can be represented as a network of conceptual relationships, where nodes correspond to disciplines and edges represent aligned conceptual pairs. The topology and intensity of this network provide insights into the degree of integration.

Sparse or weakly connected structures may indicate multidisciplinarity, where disciplines coexist without significant integration. In contrast, dense and strongly connected networks suggest higher levels of conceptual synthesis.

This conceptualization enables a direct empirical question:

> *Do diversity-based measures capture the structural properties of interdisciplinarity?*

Addressing this question requires a quantitative indicator capable of measuring structural integration.

The Interdisciplinary Integration Coefficient (IIC), introduced in this study, responds to this need by providing a scalar measure of conceptual integration based on aligned conceptual pairs. By doing so, it operationalizes structural interdisciplinarity and enables its comparison with diversity-based metrics.

This framework establishes a three-dimensional view of interdisciplinarity:

- **diversity** (distribution of disciplines),
- **interaction** (structural connections), and
- **integration** (conceptual synthesis).

The IIC specifically targets the third dimension, capturing aspects of interdisciplinarity that remain invisible to traditional diversity-based indicators.

3. Methodology

3.1 Data collection and corpus construction

The empirical analysis is based on a corpus of scientific publications retrieved through a structured and reproducible query in the Scopus database (see Appendix A). The search strategy targeted publications explicitly referring to interdisciplinarity in their title, abstract, or keywords, including both English and Spanish terms. Additional filters restricted results to university-affiliated publications published between 2015 and 2024, with at least one author affiliated with a Latin American institution. Importantly, the restriction to explicitly self-declared interdisciplinary articles provide a conservative test of the relationship between diversity and integration.

The corpus was constructed through a two-phase process combining systematic retrieval and stratified sampling, following a PRISMA-informed workflow.

In Phase 1, the initial query yielded 3,064 records. After metadata screening and removal of incomplete or inconsistent entries, 3,043 publications remained eligible for analysis. These criteria ensure that both disciplinary diversity and conceptual integration can be meaningfully computed, avoiding structurally incomplete cases.

In Phase 2, a stratified sample of 315 articles was drawn to preserve disciplinary variability while ensuring computational feasibility for concept-level analysis. This sampling strategy was designed not as a limitation, but as a methodological requirement to enable detailed conceptual–ontological processing at scale.

Additional filtering criteria were then applied to ensure the validity of both integration-based and diversity-based measurements. Articles were excluded if they: (i) contained fewer than 10 references, as insufficient citation structure limits the construction of reliable disciplinary distributions; (ii) involved fewer than two disciplinary categories, as interdisciplinarity requires cross-domain interaction; or (iii) exhibited strictly monodisciplinary content, which precludes the possibility of conceptual integration.

After filtering, 280 articles were retained for conceptual extraction and computation of conceptual integration upon the Interdisciplinary Integration Coefficient (IIC).

For comparative analysis with diversity-based indicators, a subset of 112 articles was identified, corresponding to cases for which both IIC and Rao–Stirling indices could be consistently computed using available reference and classification data.

This two-phase design ensures a balance between representativeness, analytical tractability, and statistical robustness, while maintaining consistency with PRISMA principles and enabling direct comparison between integration-based and diversity-based measures. A detailed schematic representation of the methodological workflow (corpus construction process and filtering steps) is provided in Appendix C.

- Initial retrieval (Scopus query): 3,064
- After metadata screening: 3,043
- Stratified sample: 315
- Eligible for conceptual analysis: 280
- Comparable dataset (IIC + RS): 112

3.2. Data processing and disciplinary mapping

Following corpus construction, the dataset was processed through a dual-layer analytical pipeline designed to extract both disciplinary structure and conceptual relationships.

The first layer corresponds to the bibliometric representation of interdisciplinarity. Each article was assigned to one or more disciplines using the All Science Journal Classification (ASJC) system from Scopus. These classifications were used to construct disciplinary distributions at the article level. To support distance-based diversity measures, a cognitive distance matrix was derived from SCImago Journal Rank (SJR) subject categories, enabling the computation of both simplified and full Rao–Stirling indices.

The second layer corresponds to the conceptual–ontological representation of interdisciplinarity. Textual data from each article (title, abstract, and keywords) were processed to extract core concepts. Concept identification followed a structured normalization procedure to ensure semantic consistency across the corpus, including standardization of terms and resolution of synonymous expressions.

Conceptual pairs were then constructed based on co-occurrence and semantic proximity, and each concept was mapped to its corresponding disciplinary domain. This mapping enabled the construction of a cross-disciplinary interaction network, in which nodes represent disciplines and edges represent conceptual alignments between them.

The integration of these two layers results in a unified data structure combining: (i) disciplinary distributions (used for diversity-based indicators), and (ii) conceptual relationships (used for integration-based measurement through the IIC).

This dual-layer architecture constitutes a key methodological contribution of the study. It enables the simultaneous analysis of diversity, structural interaction, and conceptual integration within a coherent and reproducible framework.

Importantly, the separation between bibliometric and conceptual layers ensures that diversity and integration are derived from methodologically independent data structures, allowing for a rigorous empirical test of their relationship.

The detailed operationalization of concept extraction and alignment procedures is provided in Section 3.4 and Supplementary Material, ensuring full transparency and reproducibility.

3.3 Mathematical formulation of the Interdisciplinary Integration Coefficient IIC

The Interdisciplinary Integration Coefficient (IIC) is defined as a structured, bounded measure of conceptual interdisciplinarity, capturing both the extent of cross-disciplinary interaction and the internal organization of conceptual integration within a scientific article. This formulation addresses a central limitation in existing interdisciplinarity metrics, which tend to emphasize disciplinary diversity while neglecting the quality of conceptual integration (Porter & Rafols, 2009; Stirling, 2007).

Let $C = \{c_1, c_2, \dots, c_K\}$ denote the set of core concepts extracted from an article through the procedure described in Section 3.4. Each concept $c_k \in C$ is associated with a subset of disciplines D_k, identified based on its epistemological role in the article (Jacobs & Frickel, 2009).

This approach aligns with perspectives that emphasize integration as a defining feature of interdisciplinarity (National Academies, 2005).

3.3.1. Concept-level disciplinary structure

For each concept c_k, let: $n_k = | D_k |$ be the number of disciplines associated with the concept.

The total number of possible cross-disciplinary pairs is:

$$M_k = \frac{n_k(n_k - 1)}{2}$$

Let L_k denote the number of **aligned disciplinary pairs**, defined as pairs of disciplines for which the article provides explicit conceptual linkage, such as shared definitions, conceptual integration, or ontological reconciliation. This notion aligns with the idea that interdisciplinarity emerges not merely from co-presence of disciplines, but from meaningful epistemic interaction (Klein, 2010).

The **concept-level integration density** is defined as:

$$\rho_k = \frac{L_k}{M_k}, \text{with } \rho_k \in [0,1]$$

If $n_k < 2$, then $\rho_k = 0$.

3.3.2. Global integration density

The global cross-disciplinary integration density is computed as:

$$\rho = \frac{1}{K}\sum_{k=1}^{K} \rho_k$$

This formulation ensures that integration is evaluated at the conceptual level, consistent with prior critiques of aggregate diversity measures that fail to capture how disciplines interact (Rafols & Meyer, 2010).

3.3.3. Structural integration component

The structural component S captures the qualitative outcomes of conceptual integration and is defined as:

$$S = \alpha\,\bar{T} + \beta\,\bar{U} + \gamma\,\bar{A} + \delta\,N$$

where:

- $\bar{T}$: conceptual transformation, reflecting whether meanings evolve through interdisciplinary synthesis,
- $\bar{U}$: emergence of shared concepts across disciplines,
- $\bar{A}$: semantic agreement among disciplinary perspectives,
- N: emergence of a new hybrid or integrative domain.

These dimensions operationalize the epistemic processes underlying interdisciplinary knowledge production, as described in foundational studies on knowledge integration (Newell, 2001; Klein, 2010).

The weights are defined as:

$$\alpha = 0.40, \beta = 0.25, \gamma = 0.25, \delta = 0.10$$

ensuring:

$$\alpha = 0.40, \beta = 0.25, \gamma = 0.25, \delta = 0.10$$

and therefore $S \in [0,1]$.

The weighting scheme reflects the relative importance of conceptual transformation as the primary mechanism of integration, while still accounting for shared concepts, semantic agreement, and the emergence of new domains. To ensure robustness, alternative weighting configurations were tested through sensitivity analysis, yielding

highly stable results and confirming that the overall behavior of the IIC is not dependent on specific parameter choices.

The operationalization of these variables is detailed in the Supplementary Material to ensure reproducibility and methodological transparency.

3.3.4. Final formulation of the IIC

The multiplicative structure of the IIC reflects the conceptual requirement that interdisciplinarity emerges only when both cross-disciplinary interaction and structural integration are present simultaneously. An additive formulation would allow high interdisciplinarity scores in cases where one component is absent, which would contradict the theoretical distinction between mere coexistence of disciplines and their effective integration.

$$IIC = \rho \cdot S$$

This multiplicative structure ensures that interdisciplinarity is only high when both:

- cross-disciplinary interaction is present, and
- such interaction results in structurally meaningful integration.

This formulation aligns with the distinction between diversity and integration, recognized in scientometric literature (Stirling, 2007; Porter et al., 2007).

3.3.5. Mathematical properties of IIC

The *IIC* satisfies the following properties:

1. **Boundedness**: $0 \leq IIC \leq 1$, facilitating comparison across articles.
2. **Sensitivity to structure**: Unlike diversity-only measures, the IIC captures how disciplines are connected at the conceptual level.
3. **Independence from disciplinary counts**: The metric does not reward the mere presence of multiple disciplines, addressing known biases in interdisciplinarity indicators (Rafols et al., 2012; Melgarejo Heredia & Cadena Vinueza,2015).
4. **Scalability**: The formulation is compatible with structured coding and computational pipelines.
5. **Non-compensability**: The multiplicative structure ensures that low values in either interaction (ρ) or structural integration (S) cannot be compensated by high values in the other component, preserving the conceptual integrity of interdisciplinarity as a joint condition.

3.3.6. Interpretation

High IIC values indicate:

- both the density of cross-disciplinary interaction and the structural quality of conceptual integration
- not only the presence of multiple disciplines, but the existence of structured epistemic synthesis across them. Conversely, low values reflect either limited interaction or the absence of meaningful conceptual integration, distinguishing fragmented interdisciplinarity from structurally coherent configurations.

Low values correspond to:

- monodisciplinary work,
- fragmented interdisciplinarity,
- or superficial co-occurrence of disciplines without integration.

3.4 Conceptual–Ontological Analysis (Melgarejo–Cadena Model)

This phase constitutes the core analytical component of the study, operationalizing interdisciplinarity as a process of **conceptual integration across disciplinary boundaries**, rather than mere disciplinary co-occurrence. This approach responds to longstanding critiques in the literature that emphasize the need to distinguish between diversity and integration in interdisciplinary research (Rafols & Meyer, 2010; Klein, 2010).

The Melgarejo–Cadena (MC) model is grounded in the premise that interdisciplinarity emerges through the **alignment, transformation, and synthesis of concepts across epistemic domains**, which requires explicit semantic and ontological articulation.

3.4.1. Construction of disciplinary glossaries

Key concepts were extracted from each article using three primary sources:

- Title
- Abstract
- Author keywords

These elements have been widely recognized as reliable proxies for capturing the semantic structure and intellectual focus of scientific publications (Callon et al., 1983; Ding et al., 2001).

Extracted concepts were normalized and organized into **disciplinary glossaries**, where each concept was associated with one or more disciplines based on its epistemological function within the article (Jacobs & Frickel, 2009).

This process enables the construction of a **concept–discipline mapping**, which serves as the basis for subsequent integration analysis.

Concept extraction followed a structured protocol combining rule-based identification and controlled normalization procedures. Terms were standardized to reduce lexical

variation, and concept boundaries were defined consistently across the corpus to ensure comparability.

3.4.2. Ontological modeling of concepts

Concepts were formalized using a lightweight ontological framework, enabling:

- representation of semantic relationships between concepts,
- identification of conceptual equivalences and divergences,
- and explicit mapping of concepts across disciplinary domains.

This step is conceptually aligned with ontology-based approaches in knowledge representation, where semantic structures are used to enable interoperability and integration across heterogeneous domains (Gruber, 1995; Studer et al., 1998).

Rather than constructing a fully formal OWL ontology, the model applies **operational ontological reasoning**, focusing on the identification of: (i) shared meanings, (ii) conceptual transformations, and (iii) alignment conditions across disciplines.

The use of a lightweight ontological framework is intentional, prioritizing operational applicability and scalability over formal ontology completeness. This approach enables the systematic identification of cross-disciplinary conceptual relationships without requiring fully formalized semantic models, which would limit feasibility at scale.

3.4.3. Conceptual matrices and integration density

For each concept c_k, the set of associated disciplines D_k is used to construct all possible disciplinary pairs:

$$M_k = \frac{n_k(n_k - 1)}{2}$$

where $n_k = \mid D_k \mid$.

Aligned disciplinary pairs L_k are identified based on explicit evidence in the article, such as:

- shared definitions across disciplines,
- conceptual bridging or synthesis,
- or ontological reconciliation.

The concept-level integration density is defined as:

$$\rho_k = \frac{L_k}{M_k}$$

The global integration density is then computed as:

$$\rho = \frac{1}{K}\sum_{k=1}^{K} \rho_k$$

This formulation captures the **degree of conceptual connectivity across disciplines**, consistent with network-based interpretations of knowledge integration (Newman, 2018; Rafols & Meyer, 2010; Melgarejo Heredia & Cadena Vinueza, 2015).

Conceptual alignment between disciplines was established only when explicit textual evidence supported a meaningful semantic relationship, such as shared definitions, cross-disciplinary reinterpretation, or integrative usage within the same analytical context.

3.4.4. Conceptual integration indicators

To capture the qualitative dimensions of interdisciplinarity, four conceptual indicators are defined:

- *T*: **Conceptual transformation**: Indicates whether a concept undergoes redefinition or reinterpretation through interdisciplinary interaction.
- *U*: **Emergence of shared concepts**: Reflects the construction of unified conceptual meanings across disciplines.
- *A*: **Semantic agreement**: Captures explicit agreement between disciplines regarding the meaning or use of a concept.
- *N*: **Emergence of a new discipline**: Identifies the creation of a hybrid or integrative domain.

These indicators correspond to key mechanisms of interdisciplinary knowledge production identified in the literature, including integration, synthesis, and epistemic negotiation (Newell, 2001; Klein, 2010).

All indicators are normalized in the range $[0, 1]$, ensuring compatibility with the mathematical formulation of the IIC. The operationalization of these structural components is in Appendix B.

Each indicator is grounded in observable textual features, ensuring that conceptual integration is not inferred abstractly but supported by explicit semantic evidence within the article.

3.4.5. Computation of the IIC

The conceptual integration score is defined as:

$$S = \alpha\bar{T} + \beta\bar{U} + \gamma\bar{A} + \delta N$$
$$IIC = \rho \cdot S$$

where:

- ρ represents the density of cross-disciplinary conceptual alignments, and
- S captures the structural quality of conceptual integration.

This formulation ensures that interdisciplinarity is only considered high when both interaction and integration are present, addressing the limitations of diversity-based metrics (Stirling, 2007; Porter et al., 2007).

3.4.6. Methodological robustness and coding protocol

To ensure methodological rigor, the conceptual–ontological analysis was conducted through a semi-structured pipeline combining computational processing and guided manual validation.

Concept extraction and normalization were supported by rule-based procedures and computational tools, enabling consistent identification of candidate concepts across the corpus. These outputs were subsequently refined through manual review to ensure semantic accuracy and contextual relevance.

The identification of conceptual alignments and the scoring of T, U, A, and N indicators were based on explicit textual evidence, following a predefined coding protocol (see Supplementary Material). To reduce subjectivity, coding decisions were guided by consistent criteria applied across all cases.

A validation step was performed on a subset of articles, where the outputs of the computational pipeline were manually reviewed to confirm the correctness of concept mapping and cross-disciplinary alignment. Ambiguous cases were explicitly documented and resolved through iterative refinement of the coding guidelines.

This hybrid approach balances scalability and interpretability, ensuring that conceptual integration is operationalized in a reproducible and systematically controlled manner, while avoiding over-reliance on fully automated semantic inference.

Importantly, this approach prioritizes methodological transparency and traceability, allowing the conceptual integration process to be systematically evaluated across the corpus.

3.5. Bibliometric Analysis (ASJC Classification, Rao–Stirling Diversity, and Network Coherence)

This phase complements the conceptual–ontological analysis by introducing a bibliometric perspective on interdisciplinarity, capturing the distribution, distance, and structural organization of disciplines referenced in each article.

While the IIC focuses on conceptual integration, this phase operationalizes disciplinary diversity, addressing the well-established distinction between diversity and integration in interdisciplinarity research (Stirling, 2007; Rafols & Meyer, 2010).

3.5.1. Disciplinary classification using ASJC

Articles were classified into disciplines using the **All Science Journal Classification (ASJC)** system, based on journal-level mapping provided by SCImago (SJR).

Let:

- N be the number of articles,
- D the number of distinct ASJC categories.

A document–discipline matrix was constructed:

$$\mathbf{M} \in \mathbb{R}^{N \times D}$$

where each entry m_{ij} represents the association between article i and discipline j.

Given that journals may be assigned to multiple ASJC categories, each article inherits multiple disciplinary labels. These were normalized to obtain a probability distribution:

$$p_{ij} = \frac{m_{ij}}{\sum_{j=1}^{D} m_{ij}}$$

where p_{ij} represents the proportion of discipline j in article i.

This approach follows standard practices in bibliometric interdisciplinarity measurement using journal-based classification systems (Porter et al., 2007; Rafols et al., 2010).

3.5.2. Rao–Stirling diversity

Rao–Stirling diversity index is widely used as a proxy for interdisciplinarity, combining three dimensions: **variety, balance**, and **disparity** (Stirling, 2007; Rafols & Meyer, 2010).

For each article i, the index is defined as:

$$RS_i = \sum_{j=1}^{D} \sum_{k=1}^{D} p_{ij}\ p_{ik}\ d_{jk}$$

where:

p_{ij}: proportion of discipline *j* in article *i*,

d_{jk}: cognitive distance between disciplines *j* and *k*.

The cognitive distance matrix $\mathbf{D} = [d_{jk}]$ was computed using **cosine distance** derived from discipline co-occurrence patterns across the corpus:

$$d_{jk} = 1 - \cos(\theta_{jk})$$

Previous studies have emphasized that interdisciplinarity involves not only diversity but also forms of epistemic synergy and integration (Leydesdorff, 2018). Moreover,

diversity-based indicators have been shown to capture features distinct from knowledge integration (Leydesdorff et al., 2019).

Rao–Stirling diversity is computed based on variety, balance, and disparity of disciplinary categories, although recent studies have highlighted limitations related to uncertainty and robustness in such indicators (Nakhoda et al., 2023).

Both simplified and distance-based formulations of the Rao–Stirling diversity were computed to ensure robustness and comparability with prior studies.

3.5.3. Network coherence

To complement diversity, **network coherence** was computed to evaluate whether the set of disciplines in an article forms a structurally integrated configuration, rather than a fragmented or disconnected set.

Following Rafols and Meyer (2010), coherence reflects the **strength and density of connections among disciplines**.

For each article, a discipline co-occurrence network was constructed, where:

- nodes represent disciplines,
- edges represent co-occurrence or relational strength between disciplines.

Network coherence was computed as:

$$\text{Coherence}_i = \frac{\sum_{j \neq k} w_{jk}}{E_i}$$

where:

- w_{jk}represents the weight of the connection between disciplines j and k,
- E_i is the number of possible edges among the disciplines present in article i.

Alternatively, when edge weights are derived from similarity measures:

$$\text{Coherence}_i = \frac{1}{\mid E_i \mid} \sum_{(j,k) \in E_i} \text{sim}_{jk}$$

where $\text{sim}_{jk} = 1 - d_{jk}$, and d_{jk} is the cognitive distance between disciplines.

This ensures that coherence increases when disciplines are **not only present but meaningfully connected**, addressing a key limitation of diversity-only indicators.

3.5.4. Complementarity with conceptual integration (IIC)

The bibliometric indicators introduced in this section capture **disciplinary structure**, while the IIC captures **conceptual integration**.

This distinction is critical:

- Rao–Stirling diversity *(RS)* measures **how many and how different disciplines are involved**,
- Network coherence measures **how structurally connected those disciplines are**,
- The IIC measures **whether those disciplines are actually integrated at the conceptual level**.

As demonstrated in prior research, diversity does not necessarily imply integration (Rafols & Meyer, 2010; Porter & Rafols, 2009).

The combined use of these indicators enables a **multi-dimensional characterization of interdisciplinarity**, distinguishing between: (i) superficial interdisciplinarity (high diversity, low integration), and (ii) and deeply integrated research (high diversity, high integration).

Within the proposed framework, these indicators occupy distinct analytical roles: Rao–Stirling diversity captures the compositional dimension of interdisciplinarity, network coherence reflects the structural interaction among disciplines, and the IIC measures conceptual integration. This distinction enables a multi-layered analysis in which each component represents a non-redundant aspect of interdisciplinary research.

In this framework, network coherence can be interpreted as an intermediate layer between diversity and integration, capturing whether disciplinary components form a structurally connected configuration prior to conceptual synthesis.

3.5.5. Methodological considerations

To ensure robustness:

- ASJC classification was applied consistently across all articles,
- multi-category journals were normalized to avoid bias,
- distance matrices were computed from empirical co-occurrence data,
- all indicators were calculated at the article level.

This approach ensures comparability across articles and scalability to large datasets, in line with best practices in scientometric analysis (Waltman et al., 2012).

The joint use of these indicators enables a direct empirical test of whether disciplinary diversity and structural interaction are sufficient proxies for conceptual integration, which constitutes the central research question of this study.

3.6. Composite Interdisciplinarity Index (IC-IDR)

While the IIC provides a direct measure of conceptual integration, it does not capture the broader compositional and structural dimensions of interdisciplinarity. The IC-IDR index is introduced to integrate these complementary aspects into a unified analytical framework.

The construction of a composite index responds to the need for a multidimensional representation of interdisciplinarity, where diversity, interaction, and integration are jointly considered. Evaluating these dimensions in isolation may lead to incomplete or misleading interpretations, particularly in cases where high diversity does not correspond to meaningful conceptual synthesis.

This integration responds to a well-documented limitation in the literature: no single metric fully captures the complexity of interdisciplinarity, as diversity, structural connectivity, and conceptual integration represent **distinct but complementary dimensions** (Stirling, 2007; Rafols & Meyer, 2010; Wagner et al., 2011).

3.6.1. Definition of the composite index

The IC-IDR is defined as:

$$IC\text{-}IDR_i = w_1 \cdot IIC_i + w_2 \cdot RS_i^* + w_3 \cdot Coherence_i$$

with:

$$w_1 = 0.50, w_2 = 0.25, w_3 = 0.25. \sum w_k = 1,$$

where:

- IIC_i: conceptual integration (Section 3.3–3.4),
- RS_i: Rao–Stirling diversity (Section 3.5.2),
- $Coherence_i$: network coherence of interdisciplinarity interactions (Section 3.5.3).

This formulation operationalizes interdisciplinarity as a composite construct combining: (i) Epistemic integration, (ii) Disciplinary diversity, and. (iii) Structural connectivity.

In this formulation, conceptual integration is explicitly prioritized, reflecting its central role in distinguishing between superficial and structurally coherent interdisciplinarity. Diversity contributes to the index but does not dominate it, preventing overestimation of interdisciplinarity based solely on disciplinary dispersion.

Sensitivity analysis confirmed that alternative weighting configurations do not substantially alter the ranking of articles, indicating that the IC-IDR index is robust to plausible variations in parameter selection.

3.6.2. Rationale for weight allocation

The weighting scheme is theoretically grounded rather than arbitrary, reflecting the epistemological hierarchy of interdisciplinarity:

- **Conceptual integration as the primary dimension (50%)**
  The IIC is assigned the highest weight because interdisciplinarity fundamentally depends on the **integration of knowledge**, not merely the coexistence of disciplines (Newell, 2001; Klein, 2010). This prioritization aligns with

foundational frameworks that define interdisciplinarity as a process of synthesis and integration.

- **Diversity as a necessary but insufficient condition (25%)**
  The Rao–Stirling diversity captures disciplinary variety, balance, and disparity (Stirling, 2007), but does not account for epistemic interaction.
- **Structural (Network) coherence (25%)**
  Network coherence evaluates the structural connectivity among disciplines (Rafols & Meyer, 2010), capturing whether disciplinary combinations form a cohesive configuration.

This weighting scheme operationalizes the principle:

$$\text{Integration} > \text{Structure} \approx \text{Diversity}$$

Ensuring that high interdisciplinarity scores require meaningful conceptual integration, not only structural or compositional diversity.

3.6.3. Normalization and comparability

To ensure comparability across indicators, all indicators are expressed on a common scale:

- $IIC \in [0,1]$ by construction (Section 3.3),
- RS values were **normalized to the interval** , using min–max scaling:
$$RS_i^* = \frac{RS_i - \min(RS)}{\max(RS) - \min(RS)}$$
- $Coherence \in [0,1]$ by definition (Section 3.5.3), computed as the average pairwise similarity between disciplines present in each article.

Thus, all components are expressed on a common scale, ensuring that weights reflect **relative importance rather than scale differences**, and the composite index remains bounded.

3.6.4. Mathematical properties

The IC-IDR satisfies the following properties:

1. **Boundedness**
$$0 \leq IC\text{-}IDR \leq 1$$
2. **Convexity**
   The index is a convex combination of normalized components, ensuring stability and interpretability.
3. **Monotonicity**
   An increase in any component (holding others constant) leads to a non-decreasing IC-IDR.
4. **Partial non-compensability**

While compensatory in structure, the dominance of *IIC* reduces the risk that high diversity or coherence alone inflate interdisciplinarity scores.

5. **Multidimensional sensitivity**
   The index captures complementary dimensions (integration, diversity, structure), enabling a richer characterization than single-metric approaches.

3.6.5. Sensitivity and robustness analysis

To assess robustness of the composite index, a sensitivity analysis was conducted by varying the weights within plausible ranges around the baseline configuration. Specifically:

- $w_1 \in [0.40, 0.60]$ for IIC,
- w_2, w_3 adjusted proportionally for diversity and coherence
- Multiple weighting scenarios were evaluated.

Robustness was assessed using:

- Spearman rank correlation, comparing alternative rankings to the baseline.
- Top-k overlap, evaluating stability among the highest-ranked articles.
- Profile agreement, based on tertile classification (low, medium, high interdisciplinarity).

Results show high stability across weighting schemes, indicating that:

- Rankings are not sensitive to moderate weight variations
- The composite structure is robust under plausible parameter changes
- Conclusions are not driven by arbitrary weighting choices.

This approach follows recommended practices for composite indicator validation (OECD, 2008; Saisana et al., 2005). The IC-IDR index enables a more nuanced evaluation of interdisciplinary research, with potential applications in research assessment, funding allocation, and the design of interdisciplinary programs. By distinguishing between diversity and integration, it provides a more reliable basis for identifying structurally meaningful interdisciplinarity.

3.6.6. Analytical workflow

The overall analytical process follows an integrated and reproducible pipeline combining concept-level and reference-based approaches to interdisciplinarity measurement.

The workflow is structured into four main stages:

Stage 1: Corpus identification and selection (PRISMA framework): The dataset was obtained through a structured Scopus query, applying inclusion criteria related to interdisciplinarity and Latin American institutional affiliation. The selection process

followed PRISMA guidelines, including identification, screening, eligibility assessment, and final inclusion of a stratified sample of articles.

Stage 2: Semantic processing and conceptual modeling: This stage operationalizes interdisciplinarity as conceptual integration. Each article was processed to extract key concepts and construct semantic alignments. This includes: (i) concept extraction, (ii) alignment construction, (iii) computation of alignment density (ρ), (iv) estimation of structural components (T, U, A, N), and (v) derivation of the Interdisciplinary Integration Coefficient (IIC).

Stage 3: Bibliometric and network analysis: In parallel, disciplinary structures were analyzed using ASJC classifications. This includes: (i) assignment of disciplines, (ii) construction of co-occurrence networks, (iii) computation of Rao–Stirling diversity, and (iv) estimation of network coherence.

Stage 4: Composite index construction and validation: All components were integrated into the composite index:

$$IC\text{-}IDR = 0.50 \cdot IIC + 0.25 \cdot RS^{*} + 0.25 \cdot Coherence$$

This stage includes normalization, correlation analysis (Spearman), group comparison tests (Welch's t-test, Mann–Whitney U), quadrant-based classification, and sensitivity analysis.

This integrated workflow ensures that conceptual, structural, and diversity dimensions are analyzed within a unified framework. A schematic representation of the pipeline is provided in Figure 9 (Appendix C). The results corresponding to each stage of this workflow are presented sequentially in Section 4.

3.7. Validation and statistical analysis

To assess the robustness and interpretability of the proposed indicators, a set of complementary statistical analyses was conducted. These analyses were designed not to test predefined causal hypotheses, but to examine the consistency, independence, and structural behavior of interdisciplinarity measures.

3.7.1. Correlation analysis

The relationship between conceptual integration (IIC) and reference-based diversity (Rao–Stirling) was evaluated using Spearman's rank correlation coefficient. This non-parametric measure was selected due to the non-normal distribution of the variables and the presence of zero-inflated values in diversity and coherence indicators.

3.7.2. Quadrant analysis

To further examine the joint behavior of integration and diversity, a quadrant-based classification was applied using median thresholds. This approach enables the identification of distinct configurations of interdisciplinarity (e.g., high diversity–low integration), allowing a more nuanced interpretation beyond linear correlation.

3.7.3. Statistical testing

Differences between groups (e.g., interdisciplinary vs. control articles, or alternative groupings derived from the data) were evaluated using Welch's t-test, which is robust to unequal variances, and the Mann–Whitney U test as a non-parametric alternative.

Homogeneity of variances was assessed using Levene's test and the Brown–Forsythe test to verify the appropriateness of parametric assumptions.

Effect sizes were estimated using Cohen's d to quantify the magnitude of differences beyond statistical significance.

These tests were used in an exploratory manner to assess whether observable group structures correspond to statistically distinguishable patterns of interdisciplinarity.

3.7.4. Composite indicator validation

The behavior of the composite index (IC-IDR) was evaluated through correlation analysis with its components (IIC, Rao–Stirling diversity, and coherence), as well as through its distribution across the quadrant-based configurations.

3.7.5. Sensitivity analysis

To assess the robustness of the composite index, a sensitivity analysis was conducted by varying the weighting scheme of its components. The stability of rankings was evaluated using Spearman rank correlations and profile agreement metrics across alternative configurations.

3.7.6. Network validation

The structural properties of the disciplinary alignment network were examined to ensure consistency between concept-level integration and network-based representations. This included the analysis of centrality patterns and the identification of core-periphery structures.

4. Results

The results are presented following the structure of the analytical workflow described in Section 3.6.6, progressing from data selection to integration analysis, diversity assessment, and composite index validation.

4.1 Descriptive Statistics of interdisciplinarity indicators

This stage corresponds to the corpus identification and selection process outlined in Stage 1 of the analytical workflow.

The analysis was conducted on a corpus of 112 comparable articles, for which conceptual integration (IIC), reference-based disciplinary diversity (Rao–Stirling), network coherence, and the composite index IC-IDR were computed.

The descriptive statistics reveal a structurally asymmetric distribution across indicators. The IIC exhibits moderate dispersion (mean = 0.525, SD = 0.156), with values ranging from 0.140 to 0.938. In contrast, both Rao–Stirling diversity and coherence display highly sparse distributions, with medians and upper quartiles equal to zero.

Therefore, the composite indicator IC-IDR is concentrated in the low-to-mid range (mean = 0.300, SD = 0.124), reflecting the dominant contribution of conceptual integration under the adopted weighting scheme.

These results indicate that, within the analyzed corpus, conceptual integration is substantially more prevalent than reference-based diversity or structural coherence, suggesting an intrinsic imbalance in how interdisciplinarity manifests empirically.

4.2 Structure and distribution of conceptual integration

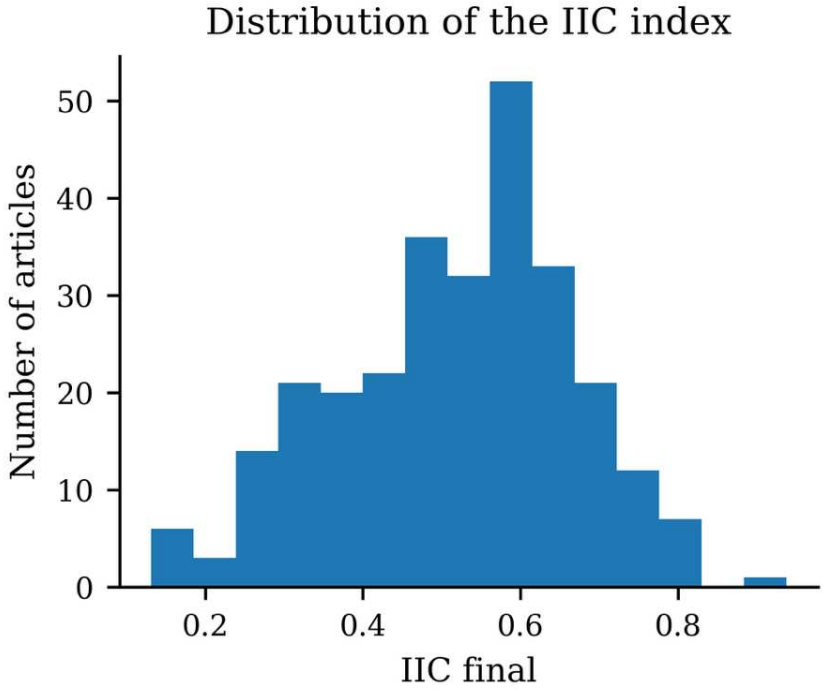
The distribution of IIC values (Figures 1 and 2) reveals a broadly unimodal pattern centered on intermediate levels of integration. The median is approximately 0.54, with an interquartile range between roughly 0.41 and 0.62.

This distribution indicates that most articles exhibit moderate levels of conceptual integration, with relatively few cases located at extreme. High-value outliers (above 0.90) confirm the existence of strongly integrative cases, although these remain exceptional.

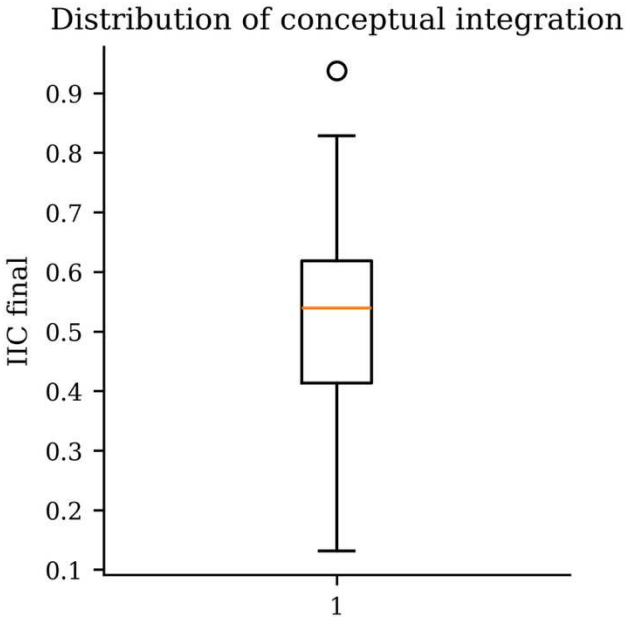
The relationship between global alignment density (ρ) and the weighted structural synthesis score (S) (Figure 5) shows a generally positive association, but with substantial dispersion. This suggests that alignment density acts as an enabling condition for integration but does not determine it mechanically.

Taken together, these results indicate that conceptual integration is a graded and structurally constrained phenomenon, dependent not only on the presence of alignments

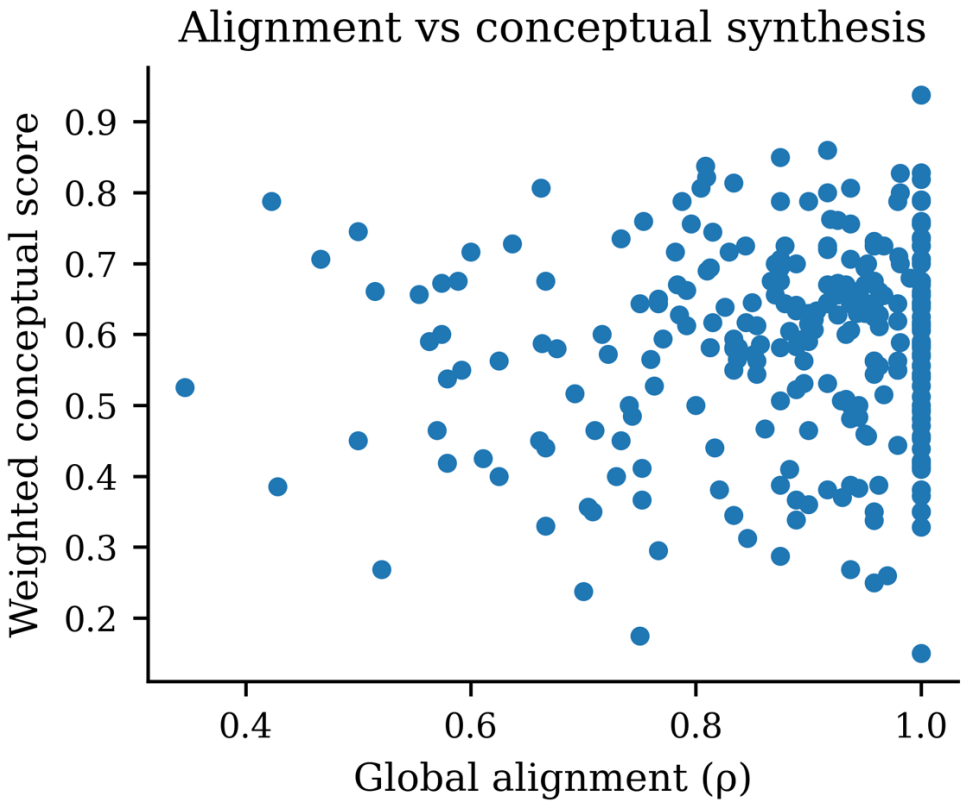
but on their qualitative transformation.



[*Figure 1. Distribution of the conceptual integration index (IIC). Histogram of the final IIC values computed as IIC=ρ·S, where ρ represents global alignment density and S the weighted structural synthesis score. The distribution shows a concentration of cases in the mid-range, indicating that most articles exhibit moderate levels of conceptual integration, with relatively few extreme values.*]



[*Figure 2: Boxplot of the conceptual integration index (IIC). Boxplot summarizing the distribution of final IIC values. The median lies around 0.54, with an interquartile range indicating moderate dispersion. The presence of high-value outliers suggests that a limited number of articles achieve unusually strong conceptual integration.*]



[*Figure 5: Global alignment density (ρ) versus weighted conceptual synthesis (S). Scatter plot showing the relationship between alignment density and the structural synthesis score. A generally positive association is observed, although substantial dispersion indicates that high alignment does not necessarily guarantee high conceptual synthesis.*]

These results correspond to the concept-level integration analysis (Stage 2 in Figure 9), capturing the structural properties of conceptual alignment.

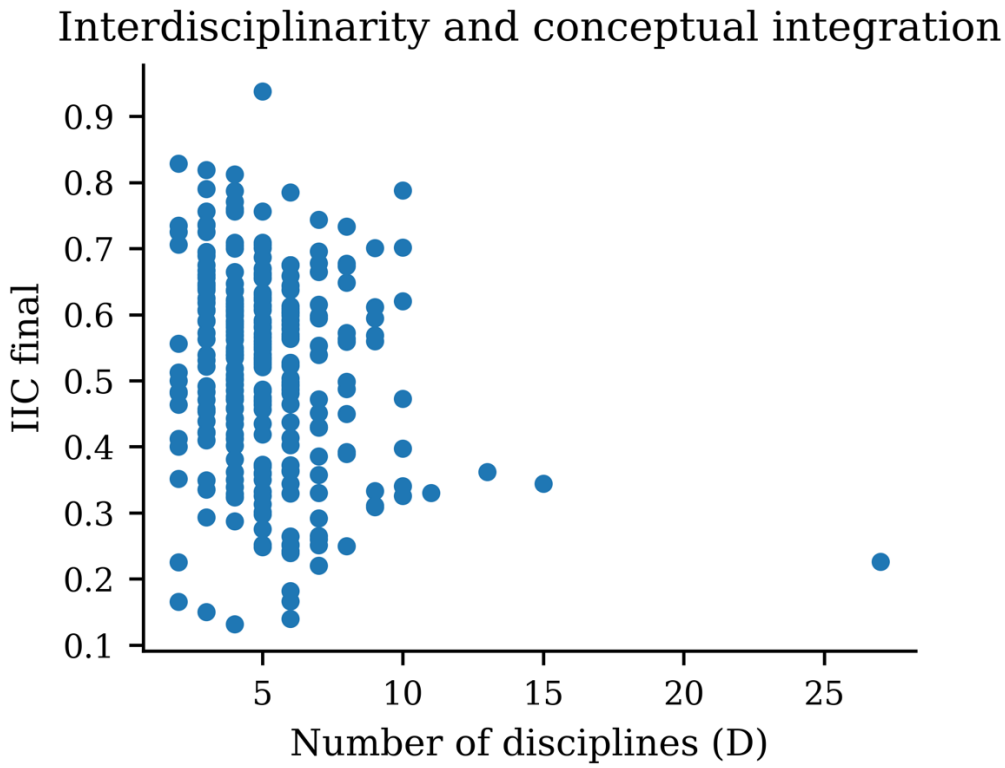
4.3. Disciplinary structure and limits of diversity

The relationship between the number of disciplines (D) and conceptual integration (Figure 6) shows no clear monotonic trend. High integration values are observed even in articles with relatively few disciplines, while some cases with broader disciplinary participation exhibit only modest integration.

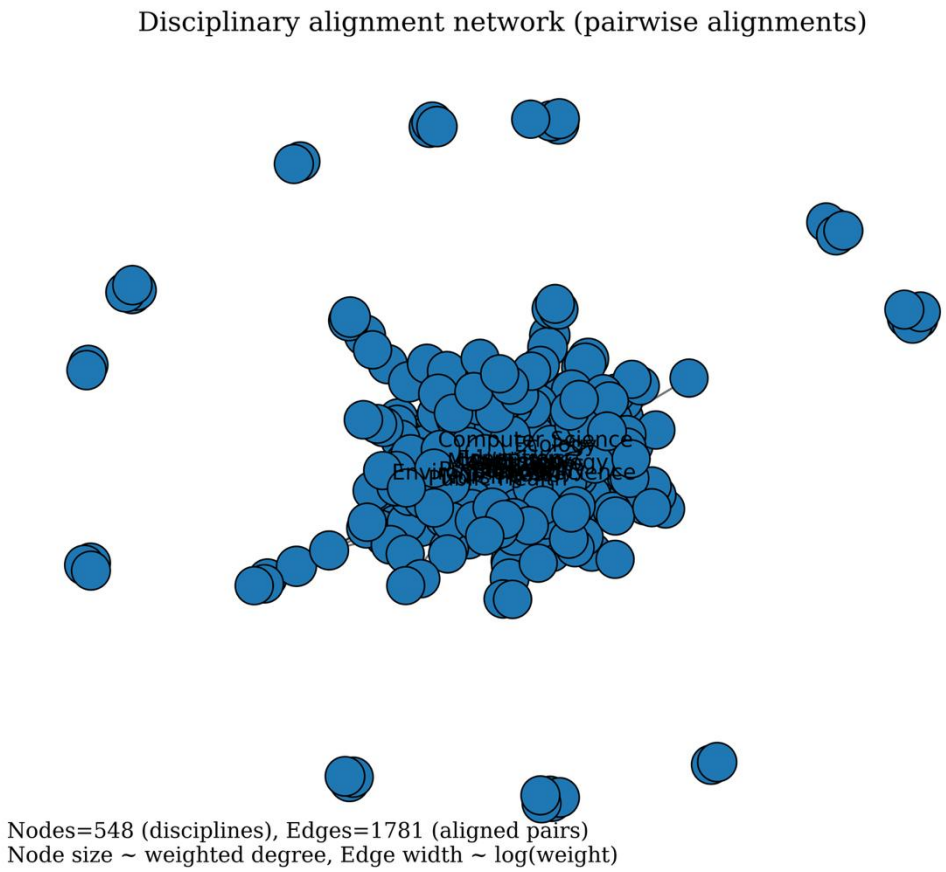
This confirms that interdisciplinarity cannot be reduced to disciplinary breadth alone but depends fundamentally on the semantic articulation and synthesis of concepts.

At the corpus level, the disciplinary alignment network (Figure 7) reveals a highly uneven structure, composed of a dense central core and multiple peripheral clusters. The most central disciplines include Education, Public Health, Sociology, and Psychology, which act as hubs of conceptual interaction.

This configuration indicates that interdisciplinarity is not diffusely distributed, but rather concentrated in specific epistemic domains that facilitate cross-disciplinary exchange.



[*Figure 6: Conceptual integration (IIC) versus number of disciplines (D). Scatter plot illustrating the relationship between disciplinary breadth and conceptual integration. The absence of a clear trend suggests that increasing the number of disciplines does not systematically lead to higher integration, supporting the distinction between diversity and synthesis.*]



[*Figure 7: Network visualization of conceptual alignments among disciplines. Nodes represent disciplines and edges represent weighted alignments. The structure reveals a dense core with peripheral clusters, indicating that interdisciplinarity is unevenly distributed across disciplinary domains.*]

This analysis reflects the diversity and network-based dimension of interdisciplinarity (Stage 3 in Figure 9).

4.4. Independence of diversity and integration and composite configuration

The relationship between conceptual integration and reference-based diversity shows a very low correlation (Spearman $\rho = 0.041$), indicating that both dimensions behave independently. This result is consistent with previous findings suggesting that different interdisciplinarity indicators capture distinct dimensions and may yield divergent results (Wang & Schneider, 2018; Leydesdorff et al., 2019).

This result constitutes a central empirical finding: diversity-based indicators do not capture conceptual synthesis. Articles with high diversity may exhibit weak integration (fragmented interdisciplinarity), while highly integrated contributions may emerge from relatively low-diversity structures.

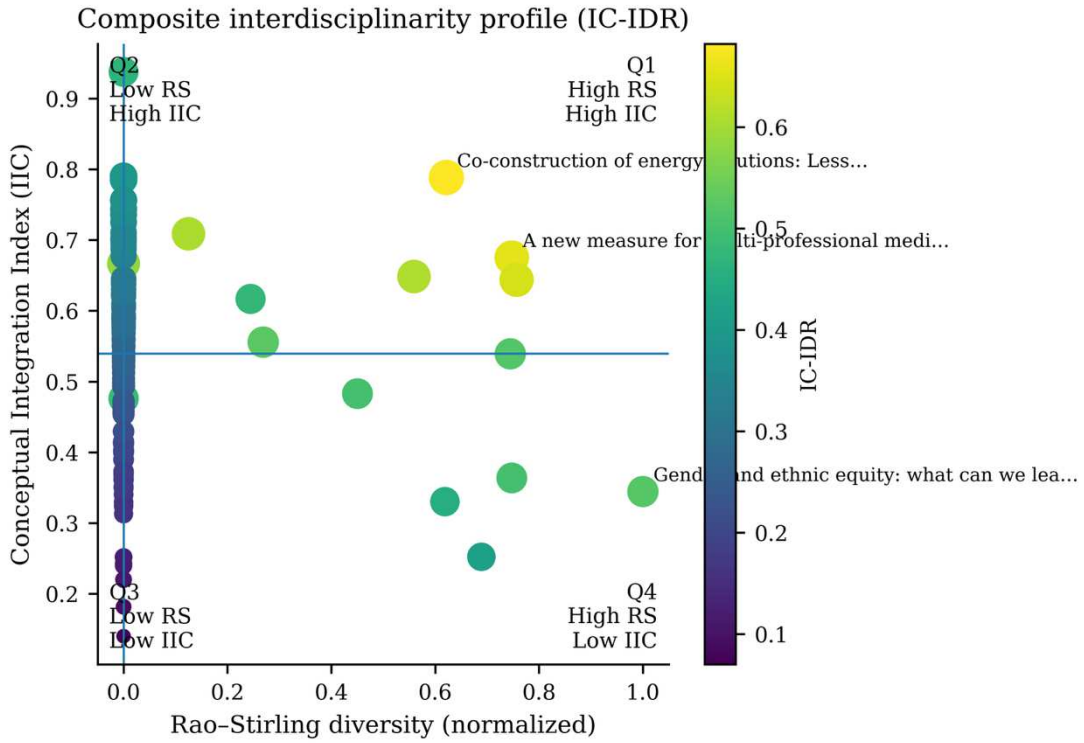
The composite representation (Figure 10) confirms this multidimensional configuration. High IC-IDR values are systematically associated with cases where both diversity and

integration are present (Q1), whereas a substantial number of cases fall into the high diversity–low integration quadrant (Q4), representing fragmented knowledge production.

Correlation analysis further supports this interpretation: IC-IDR is strongly associated with conceptual integration ($\rho = 0.788$), while maintaining only moderate associations with diversity and coherence ($\rho = 0.587$).

The absence of statistically significant differences across groups is consistent with the interpretation of interdisciplinarity as a heterogeneous and configuration-dependent phenomenon.

Overall, these results demonstrate that interdisciplinarity is not a unidimensional property, but a configuration-dependent phenomenon arising from the interaction between diversity and conceptual integration.



[*Figure 10: Composite interdisciplinarity profile (IC-IDR). Scatter plot of normalized Rao–Stirling diversity versus conceptual integration (IIC), with point size and color representing the composite index IC-IDR. Quadrants illustrate different interdisciplinarity regimes (e.g., high diversity–high integration vs. high diversity–low integration). The figure shows that high composite scores are associated with the joint presence of diversity and conceptual synthesis.*]

These findings correspond to the composite index construction and validation stage (Stage 4 in Figure 9).

5. Discussion

5.1. Interdisciplinarity beyond diversity

The results provide strong empirical evidence that interdisciplinarity cannot be adequately captured by diversity-based indicators alone. The near-zero correlation between conceptual integration (IIC) and Rao–Stirling diversity confirms that these measures operate on fundamentally different dimensions.

The dominant use of diversity-based indicators in interdisciplinarity research can be traced to foundational contributions such as Stirling (2007) and Porter and Rafols (2009), which operationalize interdisciplinarity through the distribution of references across disciplinary categories. However, these approaches do not capture whether disciplinary elements are meaningfully integrated at the conceptual level.

The present results align with prior critiques suggesting that diversity and integration should be analytically distinguished (Wang & Schneider, 2018; Leydesdorff et al., 2019) but go further by providing a formal operationalization of conceptual integration and demonstrating its empirical independence from diversity.

Thus, interdisciplinarity should be reconceptualized as a multidimensional construct in which diversity is neither a sufficient nor a necessary condition for integration.

5.2. Conceptual integration as the core dimension

The findings indicate that conceptual integration constitutes the central mechanism through which interdisciplinarity is realized. The distribution of IIC values and its dominant contribution to the composite index suggest that integration, rather than diversity, drives meaningful interdisciplinary outcomes.

Importantly, the analysis of alignment density (ρ) and structural synthesis (S) reveals that integration is not merely a function of conceptual co-occurrence. Instead, it depends on the qualitative transformation of concepts through processes such as unification, agreement, and novelty.

This distinction reinforces the idea that interdisciplinarity is not a structural property of knowledge organization alone, but an epistemic process involving the reconfiguration of conceptual relations.

In this sense, the IIC contributes a methodological advance by capturing not only the presence of cross-disciplinary elements, but the extent to which they are structurally and semantically integrated.

This perspective is consistent with earlier conceptualizations of interdisciplinarity as a process of integration rather than mere juxtaposition (National Academies, 2005).

5.3 Fragmented versus integrated interdisciplinarity

The quadrant-based analysis reveals the existence of qualitatively distinct regimes of interdisciplinarity. In particular, the identification of a substantial number of cases in the

high diversity–low integration quadrant (Q4) provides empirical evidence of what may be termed fragmented interdisciplinarity.

These cases involve the coexistence of multiple disciplinary references without effective conceptual synthesis. Such configurations may correspond to superficial or additive forms of interdisciplinarity, where disciplinary contributions remain parallel rather than integrated.

Conversely, the presence of cases in the low diversity–high integration quadrant (Q2) demonstrates that deep integration can occur within relatively narrow disciplinary configurations. This finding challenges the assumption that increasing disciplinary breadth necessarily enhances interdisciplinarity.

Together, these results suggest that the quality of interdisciplinarity depends more on the nature of conceptual articulation than on the extent of disciplinary coverage.

5.4 Implications for measurement and research policy

The proposed composite index (IC-IDR) demonstrates improved discriminative capacity by integrating conceptual and structural dimensions of interdisciplinarity. Unlike diversity-only measures, it distinguishes between superficially similar but epistemically distinct configurations.

From a methodological perspective, this supports the development of multidimensional indicators that incorporate both diversity and integration. From a policy standpoint, the findings raise important questions about current evaluation frameworks that prioritize diversity metrics without assessing conceptual synthesis.

If interdisciplinarity is to be meaningfully promoted, evaluation systems should move beyond counting disciplinary categories and instead consider how knowledge is integrated across them.

Finally, the approach presented here opens new avenues for research, including the application of concept-level integration measures to larger corpora, different scientific domains, and longitudinal analyses of knowledge production.

The reliance on diversity-based indicators in evaluation systems may therefore lead to systematic misclassification of interdisciplinary research, a concern previously raised in scientometric studies (Rafols & Meyer, 2010).

5.5 Limitations and future research

This study presents several limitations. First, the sample size for the comparable dataset (n = 112) is constrained by the availability of both conceptual and bibliometric data, which may limit generalizability. Second, the conceptual–ontological analysis involves a semi-structured coding process, which, despite validation procedures, may introduce a degree of subjectivity. Third, the focus on Latin American publications may reflect regional epistemic patterns that are not directly transferable to other scientific contexts.

Future research should extend this approach to larger and more diverse datasets, as well as explore automated methods for conceptual alignment detection.

6. Conclusions

This study provides empirical and methodological evidence that interdisciplinarity cannot be adequately captured through diversity-based indicators alone. The low correlation between conceptual integration (IIC) and reference-based Rao–Stirling diversity demonstrates that these dimensions operate independently and reflect fundamentally different aspects of knowledge production.

By introducing a concept-level measure of integration, this work advances the operationalization of interdisciplinarity beyond structural proxies. The results show that meaningful interdisciplinarity is not determined by the number or diversity of disciplines involved, but by the extent to which concepts are semantically aligned and structurally synthesized.

The identification of distinct regimes—particularly fragmented interdisciplinarity (high diversity, low integration) and focused integration (low diversity, high integration)—highlights the limitations of prevailing evaluation approaches that equate interdisciplinarity with disciplinary breadth.

The composite index (IC-IDR) further demonstrates that combining integration with diversity yields a more discriminative and theoretically grounded representation of interdisciplinarity. This reinforces the need for multidimensional frameworks capable of distinguishing between superficial and substantive forms of cross-disciplinary knowledge production.

This work contributes to a shift from diversity-based proxies toward integration-centered frameworks for understanding and evaluating interdisciplinary research. Future research should extend this approach to larger datasets, diverse scientific domains, and longitudinal analyses, to better understand the dynamics of integrative knowledge production.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data used in this study are derived from publicly available sources. The dataset of articles was retrieved from the Scopus database (Elsevier). All data used are open access and can be accessed through the Scopus platform.

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Appendix

Appendix A: Scopus Query

```
TITLE-ABS-KEY (interdisciplinary OR interdisciplinariedad)
AND PUBYEAR > 2014 AND PUBYEAR < 2025
AND (
  LIMIT-TO (AFFILCOUNTRY, "Ecuador") OR
  LIMIT-TO (AFFILCOUNTRY, "Argentina") OR
  LIMIT-TO (AFFILCOUNTRY, "Chile") OR
  LIMIT-TO (AFFILCOUNTRY, "Brazil") OR
  LIMIT-TO (AFFILCOUNTRY, "Mexico") OR
  LIMIT-TO (AFFILCOUNTRY, "Colombia") OR
  LIMIT-TO (AFFILCOUNTRY, "Peru") OR
  LIMIT-TO (AFFILCOUNTRY, "Venezuela") OR
  LIMIT-TO (AFFILCOUNTRY, "Costa Rica") OR
  LIMIT-TO (AFFILCOUNTRY, "Panama") OR
  LIMIT-TO (AFFILCOUNTRY, "Paraguay") OR
  LIMIT-TO (AFFILCOUNTRY, "Uruguay") OR
  LIMIT-TO (AFFILCOUNTRY, "Guatemala") OR
  LIMIT-TO (AFFILCOUNTRY, "Bolivia") OR
  LIMIT-TO (AFFILCOUNTRY, "Cuba") OR
  LIMIT-TO (AFFILCOUNTRY, "Spain") OR
  LIMIT-TO (AFFILCOUNTRY, "Honduras") OR
  LIMIT-TO (AFFILCOUNTRY, "Nicaragua") OR
  LIMIT-TO (AFFILCOUNTRY, "Dominican Republic")
)
AND LIMIT-TO (DOCTYPE, "ar")
AND LIMIT-TO (OA, "all")
AND (LIMIT-TO (LANGUAGE, "English") OR LIMIT-TO (LANGUAGE, "Spanish"))
```

Appendix B: Operationalization of Structural Components (T, U, A, N)

The structural component *S* of the Interdisciplinary Integration Coefficient (IIC) is defined based on four sub-indicators: **Transformation (T), Uniformity (U), Alignment (A), and Normalization (N)**. These components are computed from the network of aligned conceptual pairs extracted from each article.

B.1. Conceptual pair extraction

For each article, a set of conceptual units is identified through text processing. Concepts are normalized and paired based on:

- co-occurrence within textual units (e.g., sentences or paragraphs),
- semantic proximity,
- and cross-disciplinary mapping.

Each conceptual pair is associated with the disciplinary domains of the concepts involved, allowing the identification of **intra- and cross-disciplinary relationships**.

B.2. Transformation (T)

The transformation component measures the proportion of conceptual relationships that occur across disciplinary boundaries.

$$T_i = \frac{E_{cross}}{E_{total}}$$

where:

- E_{cross}: number of conceptual pairs linking different disciplines,
- E_{total}: total number of conceptual pairs in the article.

Interpretation: T captures the extent to which knowledge is transformed through cross-disciplinary interaction rather than remaining within a single domain.

B.3. Uniformity (U)

Uniformity measures the distribution of cross-disciplinary interactions across disciplines.

$$U_i = 1 - \sum_d p_d^2$$

where:

p_d: proportion of cross-disciplinary links associated with discipline d.

Interpretation: High U indicates that integration is not dominated by a few disciplines but distributed more evenly.

B.4. Alignment (A)

Alignment captures the intensity and density of conceptual connections between disciplines.

$$A_i = \frac{E_{cross}}{D_i(D_i - 1)}$$

where:

D_i: number of disciplines in article i,

E_{cross}: cross-disciplinary conceptual links.

Interpretation: Measures how strongly disciplines are interconnected relative to the maximum possible connections.

B.5. Normalization (N)

Normalization accounts for article size and structural variability.

$$N_i = \frac{E_{cross}}{E_{total}} \cdot \log\,(1 + E_{total})$$

(adapted in the Python code)

Interpretation: Prevents bias from:

- very short articles (few links),
- very large articles (inflated link counts).

B.6. Aggregation into structural component S

The structural component is computed as:

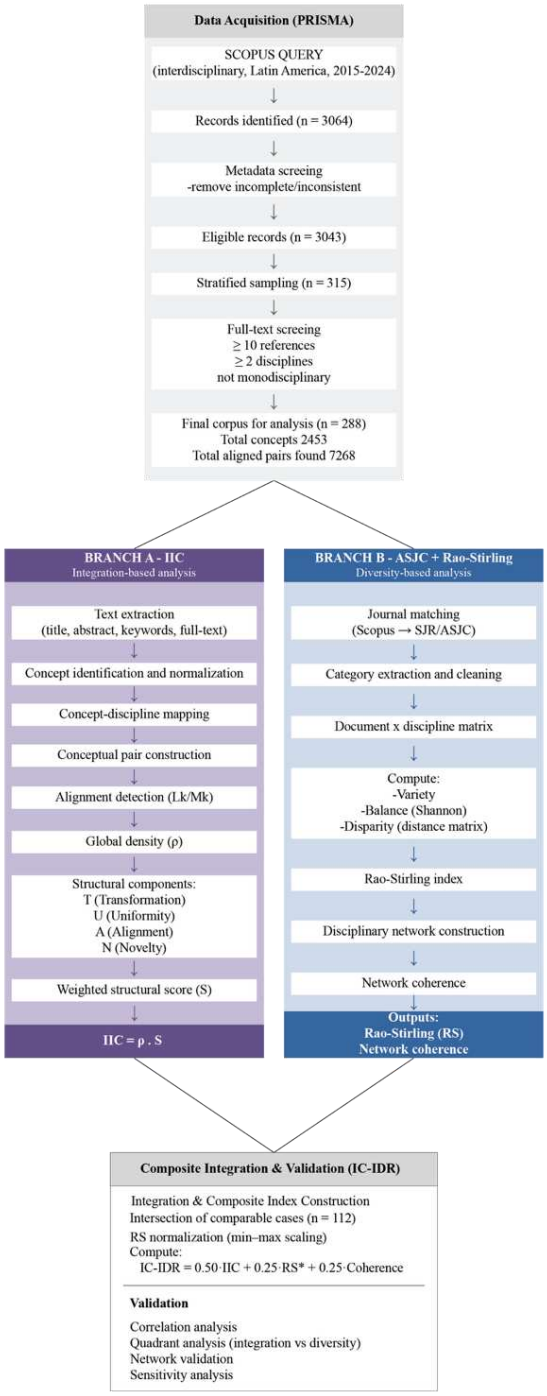
$$S_i = \frac{T_i + U_i + A_i + N_i}{4}$$

All components are normalized to $[0, 1]$, ensuring comparability.

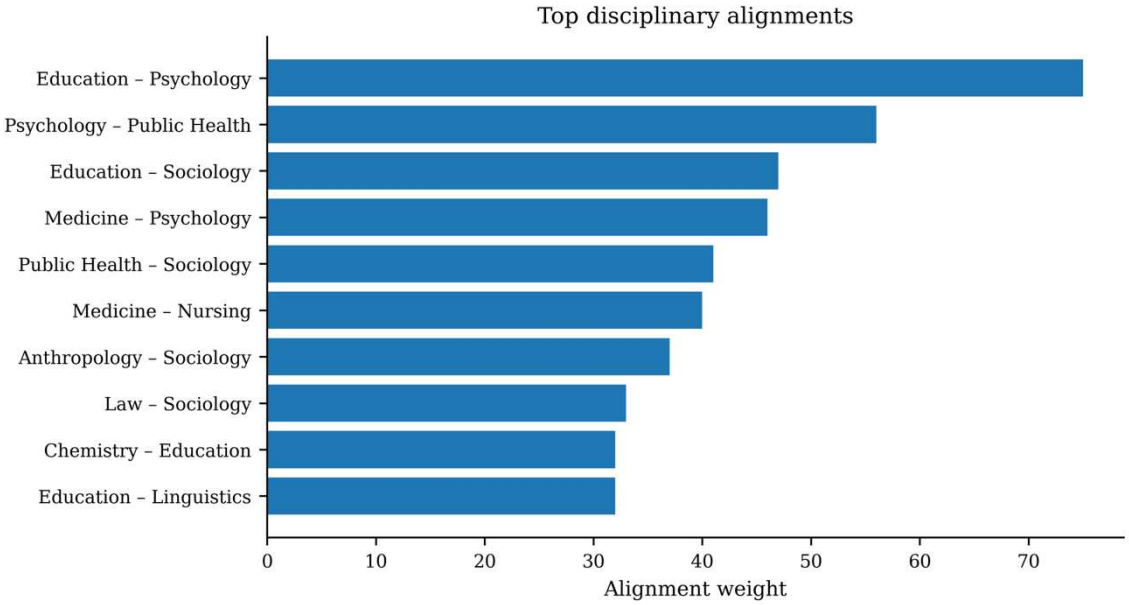
The exact implementation of these components, including preprocessing steps and parameter settings, is provided in the Supplementary Material (code repository), ensuring full reproducibility of the results.

Appendix C: Pipeline

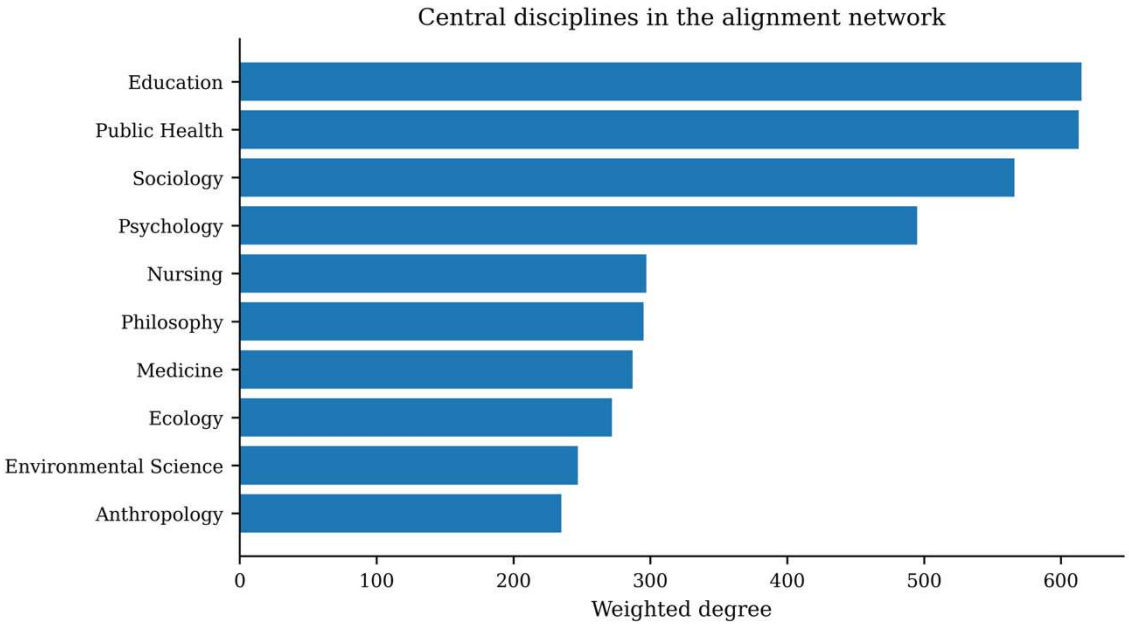
[*Figure 9. Integrated methodological pipeline for interdisciplinarity measurement. Schematic representation of the analytical workflow, structured into four stages: (1) corpus identification and selection (PRISMA-based Scopus query), (2) concept-level integration analysis (IIC), (3) diversity and network analysis based on ASJC classifications and Rao–Stirling metrics, and (4) composite index construction (IC-IDR) and validation. The empirical results associated with each stage are reported in Section 4*.]


Data Acquisition (PRISMA)
SCOPUS QUERY
(interdisciplinary, Latin America, 2015-2024)
Records identified (n = 3064)
Metadata screeing
-remove incomplete/inconsistent
Eligible records (n = 3043)
Stratified sampling (n = 315)
Full-text screeing
≥ 10 references
≥ 2 disciplines
not monodisciplinary
Final corpus for analysis (n = 288)
Total concepts 2453
Total aligned pairs found 7268
BRANCH A - IIC
Integration-based analysis
Text extraction
(title, abstract, keywords, full-text)
Concept identification and normalization
Concept-discipline mapping
Conceptual pair construction
Alignment detection (Lk/Mk)
Global density (ρ)
Structural components:
T (Transformation)
U (Uniformity)
A (Alignment)
N (Novelty)
Weighted structural score (S)
IIC = ρ . S
BRANCH B - ASJC + Rao-Stirling
Diversity-based analysis
Journal matching
(Scopus → SJR/ASJC)
Category extraction and cleaning
Document x discipline matrix
Compute:
-Variety
-Balance (Shannon)
-Disparity (distance matrix)
Rao-Stirling index
Disciplinary network construction
Network coherence
Outputs:
Rao-Stirling (RS)
Network coherence
Composite Integration & Validation (IC-IDR)
Integration & Composite Index Construction
Intersection of comparable cases (n = 112)
RS normalization (min–max scaling)
Compute:
IC-IDR = 0.50·IIC + 0.25·RS* + 0.25·Coherence
Validation
Correlation analysis
Quadrant analysis (integration vs diversity)
Network validation
Sensitivity analysis

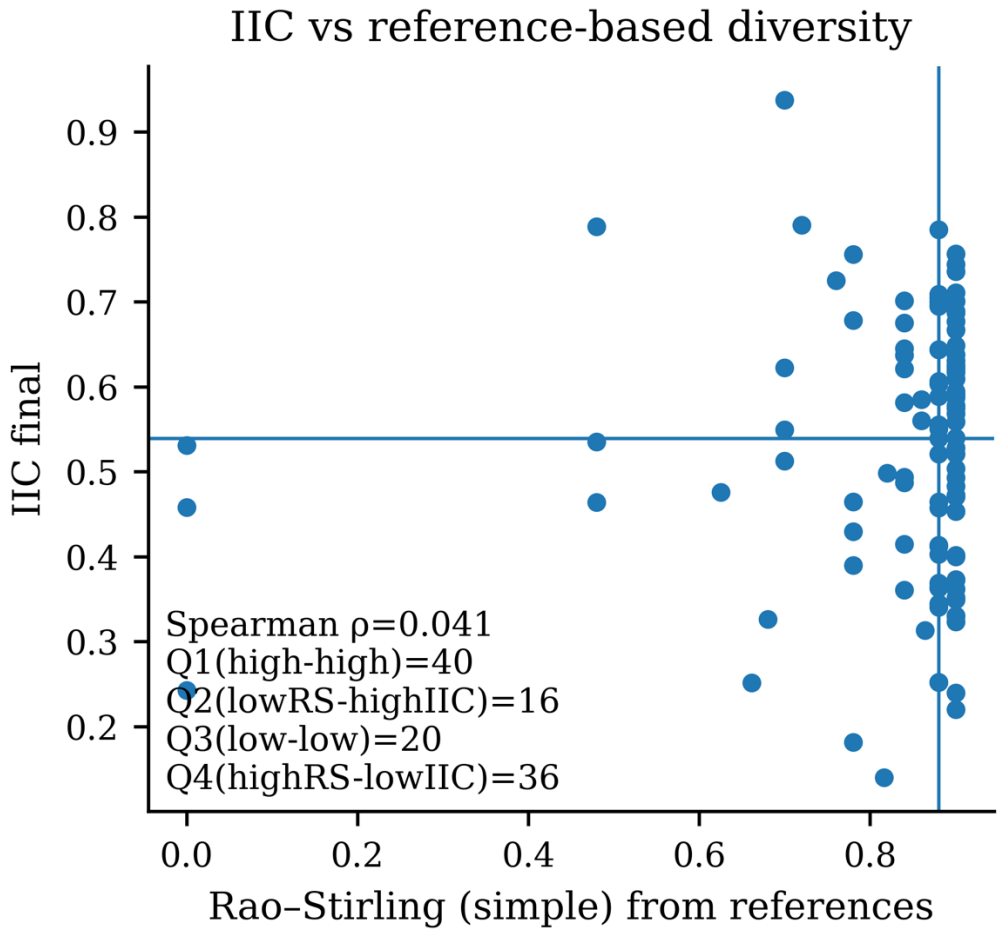
Appendix D: More figures



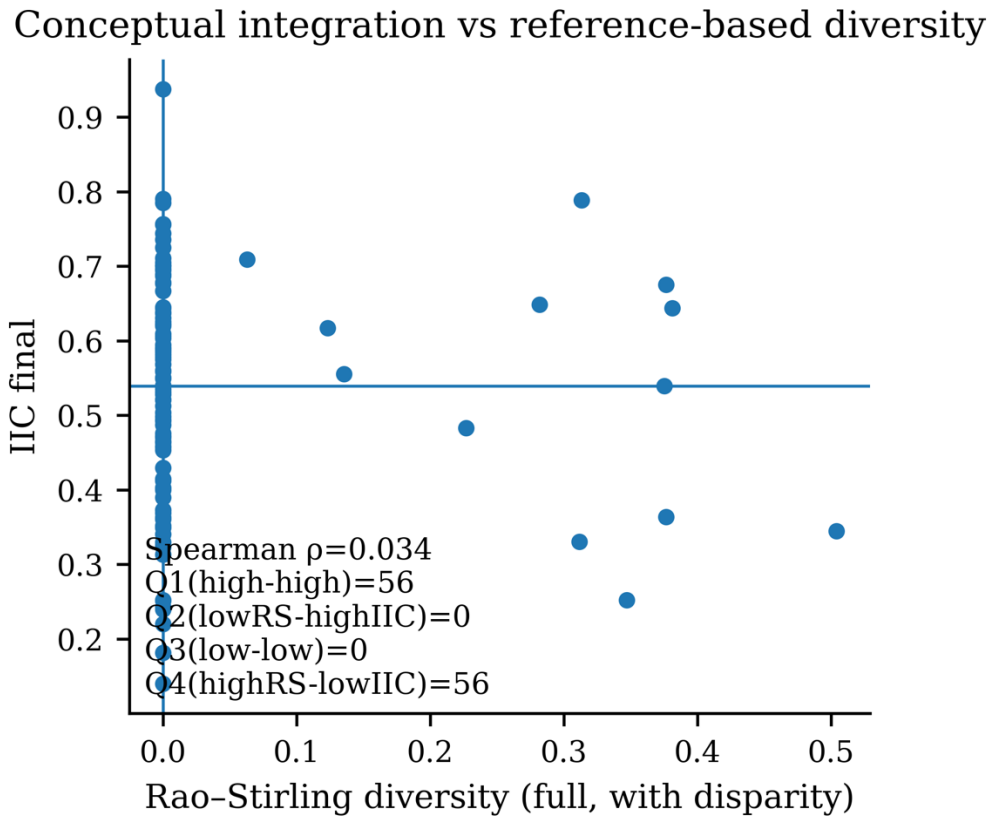
[*Figure 3: Top disciplinary alignments based on conceptual co-occurrence. Bar chart of the most frequent pairwise disciplinary alignments identified through concept-level mapping. Edge weights correspond to the number of aligned concept pairs between disciplines. The results highlight dominant interdisciplinary interactions, particularly among education, psychology, public health, and sociology.*]



[*Figure 4: Central disciplines in the conceptual alignment network. Top disciplines ranked by weighted degree centrality in the alignment network. Node importance reflects the cumulative strength of conceptual alignments with other disciplines. The results indicate that social and health-related disciplines act as central hubs of conceptual integration.*]



[*Figure 8: Conceptual integration versus reference-based disciplinary diversity. Scatter plot comparing IIC and Rao–Stirling diversity (computed from references). The vertical and horizontal lines represent median values used to define four quadrants. The Spearman correlation (ρ=0.041) indicates that conceptual integration and reference-based diversity are largely independent dimensions of interdisciplinarity.*]



[*Figure 9: Scatter plot of IIC against Rao–Stirling diversity including disparity. The negligible correlation confirms that even refined measures of diversity remain largely independent from conceptual integration, reinforcing the need for integration-based indicators*.]