

Enriching Scientific Knowledge Graph with Entropy-driven Progressive Self-Feedback Fusion (Technical Report)

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Table 1: Statistics of the SciFusion-Bench. ‘# F_{fused} ’: The total number of fused new facts (tuples) from GKG into SKG. The average neighbor structure similarity of entities in SKG and GKG, as defined in [9]. ‘#Rel. O.’: The proportion of overlapping relations in SKG and GKG.

Cluster	Dataset	Domain	# F_{fused}	Str. Sim. $\downarrow\downarrow$	Rel. O. $\downarrow\downarrow$
LS	SKGF(W-Bio)	Biomedical	12,430	8.2%	0%
	SKGF(W-Plant)	Botany	8,120	13.2%	0%
NS	SKGF(W-Mat)	Materials	11,440	5.7%	0%
SHS	DKGF(W-I)	Politics	796,254	15.4%	0%
	DKGF(Y-I)	Politics	451,158	14.0%	0%
	SKGF(W-Music)	Musicology	5,057	16.8%	0%

Abstract

To support the reproducibility and scientific rigor of “Enriching Scientific Knowledge Graph with Entropy-driven Progressive Self-Feedback Fusion”, this technical report provides essential background and extended results. Key contents include in-depth descriptions of scientific knowledge fusion tasks, precise LLM prompt engineering strategies, and a broader array of experimental results across diverse scientific domains. This document acts as a primary reference for the implementation details and the expanded empirical evidence of the Self-Fusion methodology.

Keywords

AI for Science; Scientific Knowledge Graph Fusion; Entropy-driven Progressive Self-Feedback

1 Experiments

In this section, we present a comprehensive evaluation of our framework. We begin by detailing the experimental setup, followed by an in-depth analysis of the results to demonstrate the superiority of the proposed framework in multiple scientific scenarios.

1.1 Experimental Settings

1.1.1 Benchmark Datasets. To evaluate the robustness of Self-Fusion across diverse scientific disciplines, we construct SciFusion-Bench, a multi-domain benchmark encompassing six standardized datasets. As illustrated in Table 1, each dataset follows the prior

criteria [29], where general knowledge from Wikipedia (via Wikidata or YAGO) is selectively integrated into a specialized SKG. The benchmark is categorized into three major scientific clusters:

- **Life Science (LS):** This cluster covers biological systems and molecular mechanisms. SKGF(W-Bio) integrates general molecular attributes and genetic metadata from Wikidata into PrimeKG [4], a precision medicine KG. SKGF(W-Plant) fuses Wikipedia’s botanical descriptions into the specialized taxonomy and trait records of AgroLD [19].
- **Physical Science (PS):** This cluster emphasizes the properties of physical matter. SKGF(W-Mat) identifies chemical nomenclature and physical constants from Wikidata to enrich the experimental crystal structure data in the materials project [14].
- **Social & Humanistic Science (SHS):** This cluster captures human events and culture. It includes DKGF(W-I) and DKGF(Y-I), which selectively fuse background entity facts from Wikidata/YAGO into the temporal political event streams of ICEWS [29]. SKGF(W-Music) integrates artist biographies from Wikipedia into the musicology structures of MusicBrainz [12, 23].

Detailed statistics of the entities and fused facts are provided in Table 1.

1.1.2 Benchmark Configurations. Since SKGF is a nascent task with no pre-existing specialized scientific solutions, a primary contribution of this work is to establish a comprehensive and standardized evaluation suite to facilitate future research. Following [29], we systematically adapted 22 representative methods from related fields (e.g., KGC, EA) to the SKGF setting using a unified fusion scoring protocol. These configurations are categorized as follows:

- **General-purpose Configurations.** To establish benchmark performance using universal architectures, this category employs broadly applicable methods (e.g., TransE, GNN, BERT, LLMs) rather than task-specific designs. This category of configurations is mainly based on current advanced and classic general methods, including rule-based methods (i.e., “Rule.”), such as StringMatch-F [7] and TF-IDF-F [16]; Translation-based methods (i.e., “Trans.”) such as TransE-F [3], TransH-F [17], DistMult-F [22], and ComplEx-F [18]; GNN-based methods (i.e., “GNN”)

Table 2: Main experiment results on DKG(W-I) and DKG(Y-I) datasets. Since ACC and F1 provide a comprehensive evaluation of model performance [27, 29], the best ACC/F1 results are highlighted in **bold, while the runner-up results are underlined. “*Sema.*, *Struc.*, *LLM.*” indicate the use of semantics information, structural information, and large language models, respectively.**

Benchmark Configurations	Settings	DKGF(W-I)-S1						DKGF(Y-I)-S1						DKGF(W-I)-S2						DKGF(Y-I)-S2											
		<i>Sema.</i>		<i>Struc.</i>		<i>LLM.</i>		ACC		P		R		F1		ACC		P		R		F1		ACC		P		R		F1	
<i>General-purpose</i>																															
Rule.	StringMatch-F	✓						0.496	0.160	0.002	0.004	0.498	0.286	0.003	0.005	0.498	0.192	0.002	0.003	0.498	0.308	0.003	0.005								
	TF-IDF-F	✓						0.498	0.461	0.025	0.047	0.507	0.598	0.043	0.081	0.498	0.451	0.023	0.043	0.508	0.598	0.046	0.086								
Trans.	TransE-F	✓	✓					0.649	0.668	0.596	0.630	0.588	0.782	0.244	0.372	0.637	0.662	0.560	0.607	0.575	0.772	0.212	0.332								
	TransH-F	✓	✓					0.640	0.683	0.520	0.591	0.583	0.764	0.240	0.365	0.632	0.685	0.489	0.570	0.568	0.768	0.195	0.311								
Trans.	DistMult-F	✓	✓					0.554	0.547	0.629	0.585	0.525	0.524	0.548	0.536	0.536	0.532	0.590	0.560	0.532	0.530	0.562	0.545	0.530							
	ComplEx-F	✓	✓					0.553	0.546	0.632	0.586	0.526	0.525	0.567	0.545	0.549	0.539	0.609	0.572	0.515	0.514	0.546	0.530	0.530							
GNN.	GCN-F	✓						0.485	0.487	0.572	0.526	0.501	0.501	0.793	0.614	0.493	0.494	0.582	0.534	0.498	0.499	0.796	0.613								
	TransGNN-F	✓	✓					0.490	0.491	0.505	0.498	0.465	0.465	0.477	0.471	0.486	0.487	0.507	0.497	0.468	0.468	0.481	0.474								
	Graph-Membra-F	✓	✓					0.485	0.487	0.572	0.526	0.503	0.502	0.794	0.615	0.493	0.494	0.582	0.534	0.499	0.501	0.796	0.615								
Generative.	BERT-F	✓						0.532	0.531	0.549	0.540	0.586	0.599	0.523	0.558	0.530	0.531	0.507	0.519	0.569	0.561	0.631	0.594								
	ICL-F	✓	✓	✓				0.550	0.553	0.528	0.540	0.583	0.573	0.649	0.609	0.494	0.494	0.523	0.508	0.488	0.489	0.523	0.505								
	Self-Consistency-F	✓	✓	✓				0.592	0.607	0.522	0.561	0.590	0.584	0.621	0.602	0.531	0.533	0.507	0.520	0.566	0.559	0.628	0.591								
	Self-RAG-F	✓	✓	✓				0.576	0.589	0.506	0.544	0.594	0.623	0.477	0.540	0.544	0.544	0.545	0.545	0.577	0.595	0.481	0.532								
<i>Cross-task Adaptation</i>																															
EA.	SimpleHHEA-F	✓	✓					0.490	0.492	0.507	0.499	0.493	0.493	0.503	0.498	0.492	0.492	0.507	0.500	0.477	0.477	0.481	0.479								
	ChatEA-F	✓	✓	✓				0.596	0.551	0.581	0.566	0.649	0.727	0.477	0.576	0.592	0.611	0.507	0.554	0.592	0.619	0.481	0.541								
KGC.	KG-BERT-F	✓	✓					0.523	0.522	0.546	0.534	0.516	0.515	0.531	0.523	0.507	0.507	0.515	0.511	0.503	0.503	0.481	0.492								
	KG-LLaMA-F	✓	✓	✓				0.512	0.512	0.531	0.521	0.539	0.537	0.558	0.547	0.529	0.527	0.529	0.528	0.521	0.521	0.514	0.517								
	KoPA-F	✓	✓	✓				0.558	0.556	0.577	0.566	0.561	0.556	0.602	0.578	0.549	0.547	0.564	0.556	0.541	0.543	0.522	0.532								
	PRGC-F	✓	✓					0.503	0.503	0.508	0.505	0.507	0.507	0.515	0.511	0.504	0.504	0.507	0.506	0.503	0.503	0.481	0.492								
RTE.	NoGen-BART-F	✓	✓					0.516	0.515	0.531	0.523	0.511	0.511	0.523	0.517	0.508	0.508	0.517	0.512	0.509	0.509	0.491	0.500								
	NoGen-T5-F	✓	✓					0.510	0.510	0.522	0.516	0.507	0.507	0.515	0.511	0.509	0.509	0.519	0.514	0.504	0.504	0.509	0.506								
D.	ExeFuse	✓	✓					0.680	0.673	0.708	0.690	0.661	0.615	0.717	0.662	0.655	0.627	0.683	0.654	0.633	0.634	0.682	0.657								
	Self-Fusion (Ours)	✓	✓	✓	✓			0.779	0.877	0.649	0.746	0.750	0.815	0.647	0.721	0.753	0.878	0.586	0.703	0.691	0.664	0.772	0.714								

like GCN-F [5, 28], TransGNN-F [26], and Graph-Membra-F [2]; Generative methods (i.e., “Generative.”) like BERT-F [6], ICL-F [10, 21], Self-Consistency-F [15, 20], and Self-RAG-F [1];

• **Cross-task Adaptation Configurations.** This category of configuration mainly involves improving representative methods from current related research tasks to adapt to the DKG task, including entity alignment (i.e., “EA.”), such as SimpleHHEA-F [9] and ChatEA-F [8]; knowledge graph completion (i.e., “KGC.”), such as KG-BERT-F [24, 27], KG-LLaMA-F [25, 27], KoPA-F [27] and PRGC-F [13]; and relation triple extraction (i.e., “RTE.”), like NoGen-BART-F [11], and NoGen-T5-F [11]; and domain-specific knowledge graph fusion (i.e., “D.”), like ExeFuse [29].

In addition, we report runtime (in seconds) to measure fusion efficiency. All LLMs reported in Table 2, Table 5, and Table 3 are implemented using the same model version, GPT-4 (gpt-4-0125-preview). For subsequent experiments, unless otherwise specified, GPT-3.5 (gpt-3.5-turbo-1106) is used as the default LLM configuration due to its lower computational cost. Since these datasets contain temporal information, our model prioritizes temporally proximate facts

during the *scene-aware on-demand integration* process. Hyperparameters for all configurations are tuned in the validation set using a grid search, following the ranges recommended in the original papers.

Reproducibility. In accordance with the KDD 2026 guidelines, to ensure the reproducibility of our results, we have pledged to make our source code and datasets publicly available upon the acceptance of this paper. We will apply for the “Artifacts Available” badge in the ACM Digital Library and provide a persistent DOI (e.g., via Zenodo or archived GitHub) in the camera-ready version to guarantee long-term accessibility.

1.2 Main Results

1.2.1 Performance on Standard Benchmarks (SHS). As presented in Table 2, Self-Fusion consistently outperforms all 22 baseline configurations on the widely-used ICEWS datasets (DKG(W-I) and DKG(Y-I)). Specifically, Self-Fusion achieves a substantial improvement of **20.0%** in F1-score compared to the strongest generative baseline, Self-RAG-F. A closer inspection reveals that general-purpose methods (e.g., TransE-F, GCN-F) struggle to bridge the semantic gap due to their reliance on shallow structural features. Similarly, LLM-based cross-task adaptation methods (e.g., ChatEA-F), while semantically powerful, often introduce high-entropy noise due to hallucinations. In contrast, Self-Fusion effectively mitigates these issues by coupling the *fuzzy retriever* with *progressive self-feedback*, ensuring that only scientifically relevant and structurally compatible facts are fused.

1.2.2 Generalization across Scientific Disciplines (LS & NS). To further validate the *scientific rigor* of our framework in “AI for science” scenarios, we extended the evaluation to the diverse disciplines in SciFusion-Bench, including biomedical (SKGF(W-Bio)), and

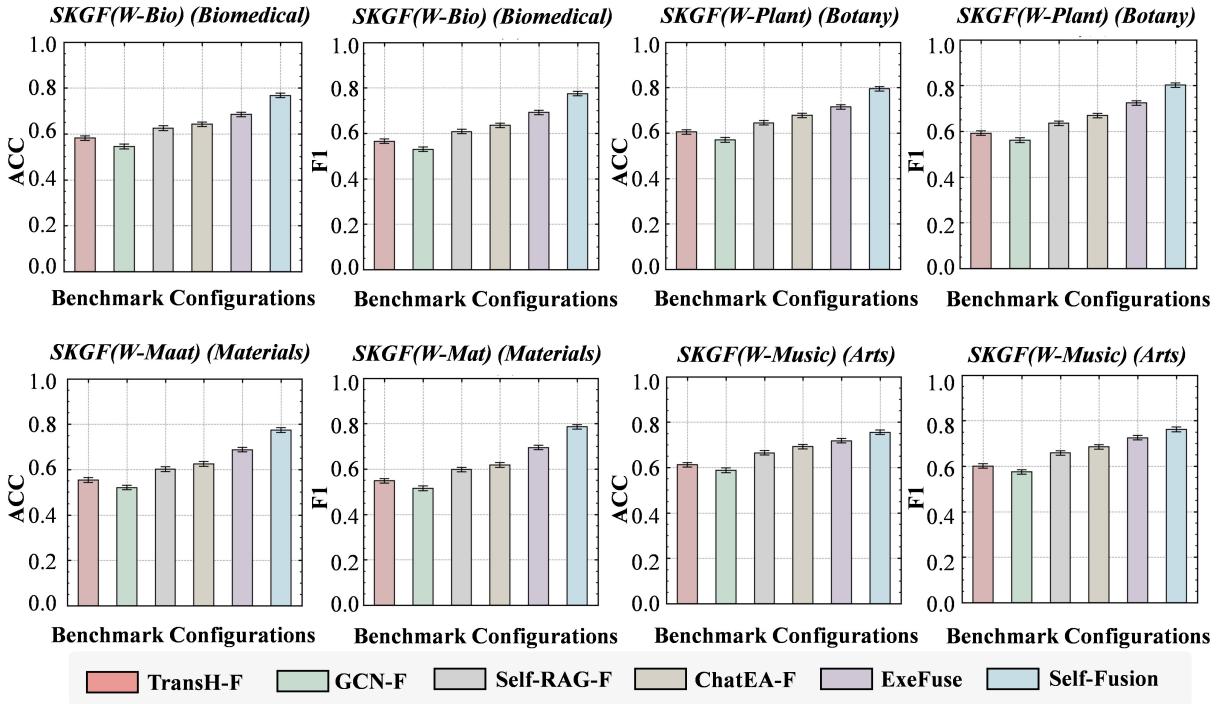


Figure 1: Comprehensive evaluation across diverse scientific disciplines in SciFusion-Bench.

materials science (SKGF(W-Mat)). As shown in Figure 1, Self-Fusion exhibits superior generalization capabilities across all domains.

Insight: “Hard Science” Demands Entropy Reduction. Crucially, we observe that the performance gap between Self-Fusion and LLM-based baselines (e.g., ChatEA-F) widens in “hard science” domains (LS & NS) compared to humanities (SHS).

- On **SKGF(W-Mat)** (materials science), Self-Fusion achieves a **13.1%** gain over the runner-up. material discovery requires strict adherence to physical laws; vague associations from GKGs (e.g., matching a material solely by name) often lead to erroneous crystal structure predictions. Our *entropy-driven* mechanism effectively filters this “scientific noise”.
- On **SKGF(W-Bio)** (biomedical), where precision is paramount to avoid false biological pathways, our model outperforms Self-RAG-F by over **27%**.

This suggests that while LLMs can handle the ambiguity of social sciences (e.g., SKGF(W-Music)), they fail to capture the *deterministic mechanisms* required by rigorous scientific domains without the explicit entropy reduction constraints imposed by Self-Fusion.

1.3 Ablation Study

To rigorously validate whether Self-Fusion successfully bridges the *Scientific Knowledge Entropy Gap*, we conducted a comprehensive ablation study on DKG(W-I)-S1 (see Table 3). Instead of merely checking module existence, we analyze how each component contributes to scientific rigor from three perspectives: macro-level entropy management, micro-level structural decoupling, and closed-loop self-verification.

Table 3: Ablation study on DKG(W-I)-S1. “Avg.”: average of ACC and F1. “Δ”: relative performance drop in Avg. compared to the full model.

Variant	DKGF(W-I)-S1			Δ
	ACC	F1	Avg.	
Self-Fusion (Full Framework)	0.779	0.746	0.763	-
<i>RQ3.1: Impact of Macro-Stages (Entropy Management)</i>				
w/o Fuzzy Retriever (Stage I)	0.583	0.554	0.569	-25.4%
w/o Progressive Fusion (Stage II)	0.502	0.515	0.508	-33.4%
<i>RQ3.2: Retrieval Mechanism (Semantic-Structure Decoupling)</i>				
w/o Meta-knowledge Line Graph	0.684	0.655	0.670	-12.2%
w/o Structural Perception	0.714	0.669	0.691	-9.4%
w/o Semantic Retrieval	0.608	0.576	0.592	-22.4%
<i>RQ3.3: Fusion Strategy (Self-Feedback Loop)</i>				
w/o Scene-aware Integration	0.507	0.522	0.515	-32.5%
w/o Scene Generation (Gen)	0.533	0.530	0.531	-30.4%
w/o Graph Reconstruction (Recon)	0.593	0.558	0.576	-24.5%

1.3.1 Necessity of Dual-Stage Entropy Management. We first verify the fundamental hypothesis that SKGF requires both entropy maximization (retrieval) and entropy reduction (fusion).

- **Impact of Fuzzy Retriever (Stage I):** Removing the retrieval module causes a 25.4% performance drop. This confirms that without a high-recall “entropy maximization” mechanism, the system fails to capture latent scientific hypotheses hidden in the high-entropy GKG, leading to a loss of valuable context.
- **Impact of Progressive Fusion (Stage II):** Removing the progressive fusion stage results in the most significant drop (Δ -33.4%). This indicates that blindly merging retrieved

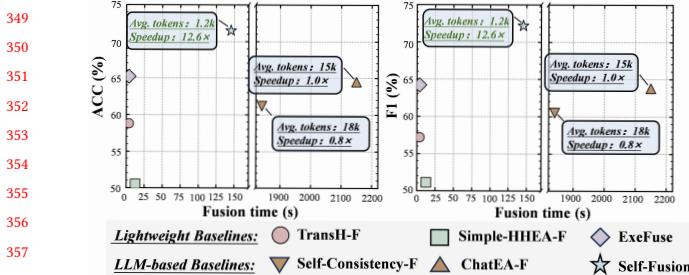


Figure 2: Efficiency and scalability analysis on the AI4S dataset SKGF (W-Mat). We compare the trade-off between inference cost and performance. “Speedup”: relative speed improvement compared to the LLM-based baseline.

facts—without the “entropy reduction” process of alignment and verification—introduces severe noise. It proves that the core challenge of SKGF is not just *finding* knowledge, but *adapting* its granularity to the scientific domain.

1.3.2 Decoupling Structure and Semantics in Retrieval. Scientific knowledge is complex; relying on semantics alone is insufficient. We analyze the design of the *Fuzzy Retriever*:

- **Meta-knowledge Line Graph:** Transforming the KG into a line graph brings a 12.2% gain. This validates that decoupling edge-centric scientific facts into node-centric representations allows for more precise feature interaction, which is critical for complex scientific relations.
- **Structure vs. Semantics:** While removing semantic retrieval causes a sharp drop (-22.4%), removing structural perception also leads to a 9.4% decline. This demonstrates that Self-Fusion successfully captures the “topology of science” (e.g., interaction networks) alongside textual descriptions, resolving the *Ambiguity of Scientific Relevance*.

1.3.3 Effectiveness of Self-Feedback Loop. Finally, we examine the *Progressive KG Fusion* mechanism, which acts as a “virtual peer review” process.

- **Scene-aware Integration:** Removing the on-demand integration leads to a failure in filtering irrelevant noise (Δ -32.5%). This highlights the importance of context-aware filtering in maintaining the purity of the SKG.
- **The Feedback Cycle (Gen & Recon):** Breaking the feedback loop by removing either Scene Generation (-30.4%) or Graph Reconstruction (-24.5%) severely degrades performance. This finding is critical for AI4Science: it proves that the *Data Self-Feedback Mechanism* effectively simulates scientific verification. If a fused fact cannot be consistently regenerated into a valid scientific scene (Generation) and reconstructed back (Recon), it is likely a hallucination or a granularity mismatch. The closed-loop design ensures that only low-entropy, deterministic knowledge is fused.

1.4 Efficiency Analysis

We evaluate the computational efficiency of Self-Fusion on the material science dataset SKGF (W-Mat), focusing on the trade-off between scientific accuracy and resource consumption. As shown in

Table 4: Diagnostic analysis on the auxiliary task “Relevant Scientific Entity Discovery (RSED)”.

Models	DKGF(W-I)-S1			DKGF(Y-I)-S1		
	ACC	F1	Avg.	ACC	F1	Avg.
DistMult-F	0.975	0.835	0.905	0.946	0.787	0.866
Self-RAG-F	0.970	0.785	0.878	0.936	0.721	0.829
ChatEA-F	0.973	0.806	0.889	0.938	0.719	0.828
ExeFuse	0.982	0.871	0.927	0.958	0.823	0.890
Self-Fusion	0.986	0.892	0.939	0.965	0.848	0.907

Figure 2, we compare our framework against two distinct categories: (1) *Lightweight Baselines* (e.g., TransH-F), which are computationally negligible but fail to capture complex scientific logic; and (2) *LLM-based Baselines* (e.g., ChatEA-F), which rely on brute-force prompting and suffer from prohibitive latency.

Self-Fusion achieves a superior **Performance-to-Cost Ratio**. Unlike ChatEA-F which consumes massive tokens (~18k/fact) via redundant iterative reasoning, our *Entropy-driven* paradigm acts as a strategic filter. It selectively activates the generative fusion module only when the *Fuzzy Retriever* identifies high-value candidates, effectively “pruning” the computational graph. Consequently, Self-Fusion reduces token consumption by 93% and achieves a **12.6× speedup** compared to LLM-based agents, while strictly outperforming them in accuracy (Avg. 0.719 vs. 0.642). This validates that our framework successfully bridges the gap between the speed of embedding-based models and the reasoning depth of foundation models, making it a scalable solution for large-scale AI4Science applications.

1.5 Relevant Scientific Entity Discovery (RSED)

Accurate identification of specialized, scientific domain-relevant entities serves as the cornerstone for effective knowledge fusion. We evaluate this capability through the diagnostic **RSED** task [29]. As shown in Table 4, Self-Fusion consistently outperforms both the retrieval baseline (Self-RAG-F) and the previous SOTA domain fusion method (ExeFuse).

Notably, while ExeFuse achieves high accuracy, Self-Fusion yields a significant improvement in F1-score (e.g., **0.892** vs. 0.871 on DKGF (W-I)). This indicates that our *Entropy-driven Fuzzy Retriever* effectively balances precision and recall, capturing latent structural isomorphisms that rigid alignment methods miss. Crucially, this superior capability in “finding the right needle in the haystack” directly correlates with the main results in Table 2, where Self-Fusion achieves a 20% performance gain. The *Data Self-Feedback* loop plays a pivotal role here, iteratively filtering out high-entropy noise (irrelevant entities) that would otherwise propagate errors to the downstream fusion stage.

1.6 Inductive Generalization for Scientific Discovery

In the realm of AI for Science, the capability to reason about novel entities (e.g., newly synthesized compounds or emerging events) is more critical than merely recalling known facts. To verify that

Table 5: Inductive generalization analysis on DKG(W-I)-S1.
We simulate an inductive scientific discovery scenario by evaluating on “Seen” (observed entities) vs. “Unseen” (novel entities) subsets. Best results are bolded.

Model	Seen (Memorization)		Unseen (Discovery)		Overall	
	ACC	F1	ACC	F1	ACC	F1
DistMult-F	0.563	0.623	0.491	0.340	0.554	0.585
Self-RAG-F	0.565	0.570	0.594	0.372	0.576	0.544
ChatEA-F	0.615	0.610	0.675	0.429	0.632	0.589
Self-Fusion	0.782	0.751	0.776	0.730	0.779	0.746

Self-Fusion learns transferable *scientific logic* rather than overfitting to specific entity embeddings, we evaluate performance in an **Inductive Setting**.

Setup. We partition the test facts into **Seen** (transductive) and **Unseen** (inductive) subsets. A fact is classified as *Unseen* if it contains entities not present in the training graph. This rigorously simulates an “inductive Discovery” scenario where the model must fuse knowledge for entirely new scientific objects.

Results & Analysis. As detailed in Table 5, distinct performance patterns emerge:

- **Baselines suffer from “embedding overfitting”:** Methods like DistMult-F and ChatEA-F show a sharp performance decay on the *Unseen* subset (e.g., ChatEA-F’s F1 drops from 0.610 to 0.429). This indicates they heavily rely on memorizing entity-specific features observed during training.
- **Self-Fusion demonstrates “structural invariance”:** In contrast, Self-Fusion maintains robust performance on Unseen data (F1 **0.730**), significantly outperforming the best baseline by over **70%**. This confirms that our *entropy-driven* framework successfully captures generalized topological patterns and causal mechanisms (e.g., “how a drug inhibits a target”) that hold true regardless of the specific entities involved. This inductive capability is pivotal for applying SKGF to dynamic, open-world scientific frontiers.

2 Conclusion and Future Work

In this work, we explore SKGF, aiming to enrich specialized SKGs with massive general knowledge. We identify the Scientific Knowledge Fusion Rigor as the core challenge which requires discerning latent scientific cues from general noise and crystallizing them into deterministic scientific facts. To address this, we propose Se If-Fusion, an entropy-driven framework that simulates scientific reasoning. The core idea is to employ a fuzzy retriever for entropy maximization and a self-feedback Fusion module for progressive entropy reduction to ensure determinacy. We also construct Sci Fusion-Bench spanning multiple scientific disciplines. Extensive experiments demonstrate that Self-Fusion consistently outperforms 22 baselines. In the future, we plan to extend our framework to support multi-modal scientific data.

3 Limitations and Ethical Considerations

While our framework demonstrates efficacy across multiple scientific domains, its performance remains partially dependent on the structural density of the source general knowledge graphs. Regarding ethical considerations, all datasets in this study, including

those within the SciFusion-Bench, are derived from established, high-quality public scientific repositories (e.g., Wikidata/YAGO and specialized SKGs) that have undergone prior peer-validation and experimental verification. This work adheres to all data privacy and intellectual property regulations, poses no known biosafety or ethical risks, and aims solely to accelerate transparent and reproducible scientific discovery through AI-driven knowledge integration.

4 GenAI Disclosure

During the preparation of this work, the authors utilized Large Language Models (specifically GPT, Claude, and Gemini) for grammar checking and stylistic refinement. Furthermore, LLMs were integrated into our research methodology as part of the LLM-based approach presented in this paper. All AI-assisted outputs were rigorously scrutinized and validated by the authors. This usage complies with ACM’s policies on authorship, and the authors remain fully responsible for the content and integrity of the final work.

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