ExpandR: Teaching Dense Retrievers Beyond Queries with LLM Guidance

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Abstract

Large language models (LLMs) have demonstrated significant potential in enhancing dense retrieval through query augmentation. However, most existing methods treat the LLM and the retriever as separate modules, overlooking the alignment between generation and ranking objectives. In this work, we propose **ExpandR**, a unified LLM-augmented dense retrieval framework that jointly optimizes both the LLM and the retriever. ExpandR employs the LLM to generate semantically rich query expansions, which are leveraged to enhance the retriever's training. Simultaneously, the LLM is trained using Direct Preference Optimization (DPO), guided by a carefully designed reward function that balances retrieval effectiveness and generation consistency. This joint optimization paradigm enables mutual adaptation between the LLM and the retriever, resulting in query expansions that are both informative and well-suited for retrieval. Experimental results on multiple benchmarks show that ExpandR consistently outperforms strong baselines, achieving more than a 5% improvement in retrieval performance. All codes are available at `https://github.com/NEUIR/ExpandR`.

1 Introduction

Dense retrievers (Karpukhin et al., 2020; Xiong et al., 2021a) encode both queries and documents into the same embedding space, enabling efficient similarity-based retrieval via approximate KNN search (Johnson et al., 2019). While effective, their performance remains highly sensitive to the quality of the input query. In practice, user queries (Belkin et al., 1982; Ingwersen, 1996) are often short and ambiguous, leading to a significant semantic gap between the query and relevant documents, making it challenging for dense retrievers to accurately capture the underlying information need.

Recent advances in Large Language Models (LLMs) (Wei et al., 2022a,b; Chen et al., 2025; Huang et al., 2025b) offer promising solutions to this challenge through query augmentation. Existing methods along this line of research can be categorized into two groups. The first direction leverages LLM-generated reformulations as supervision signals to train dense retrieval models, typically through contrastive training (Zhang et al., 2025; Ma et al., 2025) or ranking probability distillation (Shi et al., 2024; Kim and Baek, 2025). However, the effectiveness of this approach is constrained by the limited capacity and scalability of dense retrievers (Fang et al., 2024). The second direction focuses on augmenting dense retrievers by prompting LLMs to generate additional terms at inference time (Wang et al., 2023a; Mackie et al., 2023). These terms aim to increase lexical overlap with relevant documents, thereby reducing the semantic gap between queries and documents. While such expansions are often semantically rich, they are typically misaligned with the retriever, as the LLM is not explicitly optimized for retrieval objectives. As a result, the retriever struggles to effectively utilize the LLM-augmented content.

In this work, we propose **ExpandR**, a unified LLM-augmented dense retrieval framework that jointly optimizes both the LLM and the dense retriever. ExpandR first prompts the LLM to generate semantically enriched query expansions, which enhance query representations and improve the retriever's ability to rank relevant documents. Rather than treating the LLM and retriever as separate modules, ExpandR integrates generation and retrieval under a shared training objective—promoting higher ranks for ground-truth documents given a query. Specifically, we optimize the dense retriever via contrastive training, and train the LLM using Direct Preference Optimization (DPO) with a combination of self-consistency and retrieval-based

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rewards. Through this joint optimization, the two components mutually reinforce each other, leading to more effective expansions and improved overall retrieval performance.

Our experiments on the BEIR benchmark (Thakur et al., 2021) demonstrate the effectiveness of ExpandR, yielding over a 5.8% improvement in supervised dense retrieval. Further analysis shows that the query expansions generated by ExpandR lead to better alignment with relevant documents compared to those from baseline methods. By jointly leveraging self-consistency and retrieval-based rewards, the LLM is better optimized to generate expansions that are both semantically rich and retriever-aligned. Specifically, the self-consistency reward encourages the LLM to generate content that is semantically closer to the ground-truth document, while the retrieval-based reward captures the retriever's ranking behavior. Together, these rewards guide the LLM to produce expansions that are both relevant and retriever-friendly.

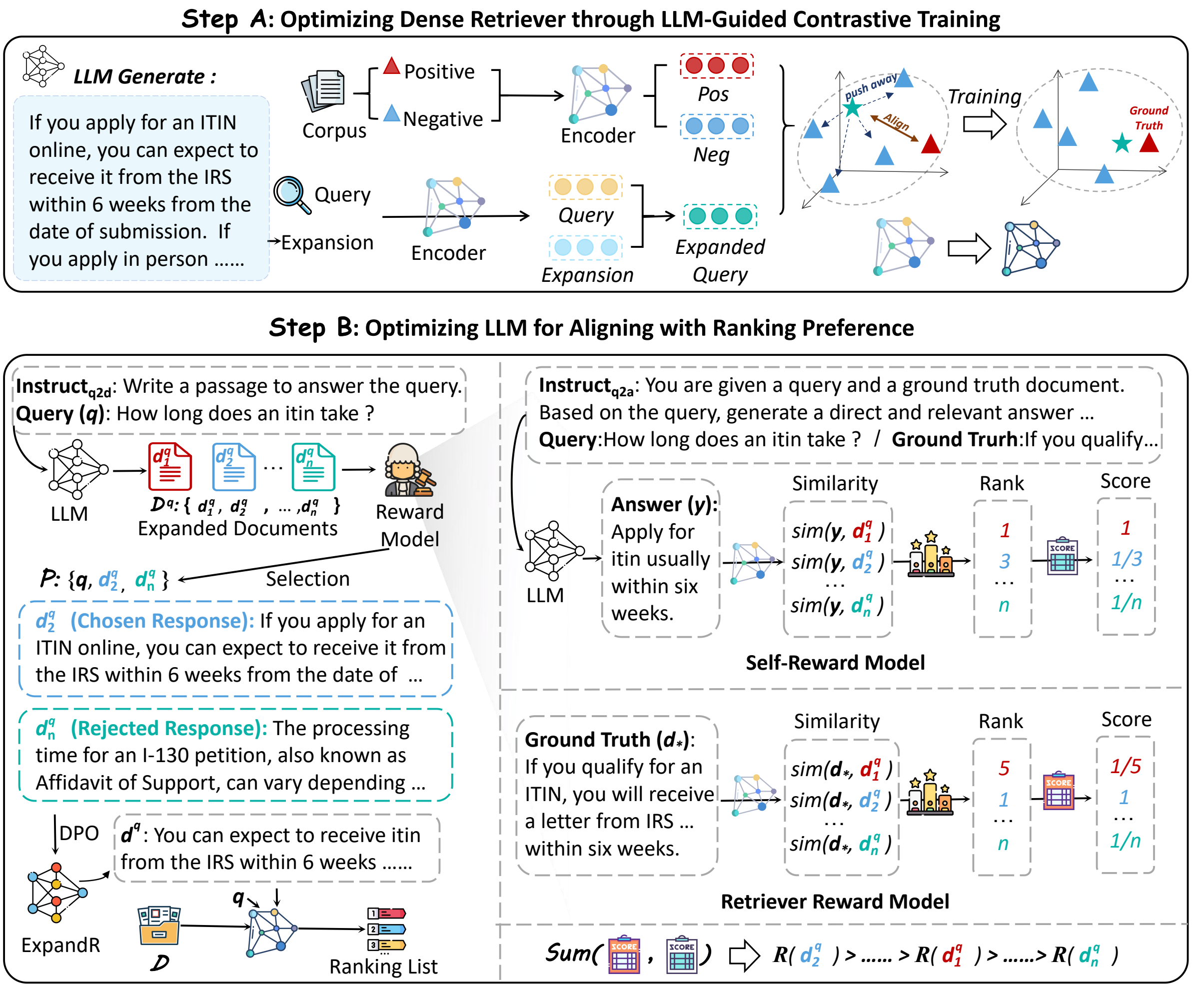
2 Related Work

Dense retrievers (Xiong et al., 2021a; Izacard et al., 2021; Yu et al., 2021; Xiong et al., 2021b; Li et al., 2021, 2025) conduct semantic matching by encoding queries and documents into a shared embedding space, thereby alleviating the vocabulary mismatch problem (Belkin et al., 1982). To further improve the quality of semantic matching, recent work has focused on refining this embedding space through contrastive learning with relevance supervision (Karpukhin et al., 2020; Zhan et al., 2021) or leveraging weakly supervised training signals (Xie et al., 2023). While effective, a persistent bottleneck in information retrieval lies in the quality of the user-issued queries themselves (Jiang et al., 2025). In particular, queries are often underspecified, ambiguous, or semantically incomplete, which limits the retriever's ability to accurately locate relevant content (Belkin et al., 1982; Ingwersen, 1996).

Recent advances in LLMs (Huang et al., 2024a; Zhao et al., 2024; Liu et al., 2024; Liu et al.) offer new opportunities to address this issue by leveraging their rich knowledge and powerful generative capabilities to enrich or reformulate user queries (Yu et al., 2020; Lin et al., 2020; Ye et al., 2023). These augmented queries are often used as supervision signals or distillation targets to train dense retrievers more effectively. For instance, methods such as LLM-QL (Zhang et al., 2025) and DRAMA (Ma et al., 2025) propose leveraging LLMs to generate new queries or training triplets for dense retriever optimization. RePlug (Shi et al., 2024) has been proposed to distill the knowledge of LLMs into a lightweight retriever. While these approaches enhance supervised retrieval performance, they mainly focus on query synthesis, often overlooking the limited semantic expressiveness of the original queries (Wang et al., 2023b). Moreover, their effectiveness is fundamentally constrained by the limited capacity and scalability of dense retrievers (Huang et al., 2024b).

LLM-based query expansion has emerged as a widely adopted approach for query augmentation (Lei et al., 2024; Xia et al., 2024), effectively enriching the semantic content of original queries. These methods prompt LLMs to generate query-related documents (Wang et al., 2023a; Jagerman et al., 2023; Gao et al., 2023), leverage Chain-of-Thought (CoT) reasoning results (Wei et al., 2022b; Trivedi et al., 2023), or utilize specific keywords (Li et al., 2024b; Jagerman et al., 2023) to expand queries, thereby enhancing the ranking capabilities of lexical matching based retrieval models (Jagerman et al., 2023; Wang et al., 2023a), dense retrieval models (Wang et al., 2023a), and reranking models (Li et al., 2024b). However, these LLM-generated expansions are often directly incorporated into the retrieval process without retraining or adapting the retriever. Consequently, the retriever fails to fully leverage the enriched signals of LLMs, resulting in limited improvements in retrieval performance (Wang et al., 2023a).

Moreover, existing approaches that incorporate LLMs into retrieval systems often train the LLM (Jiang et al., 2025) or the retriever independently (Kim and Baek, 2025), resulting in preference misalignment between the generation and retrieval components. Some works, such as RaFe (Mao et al., 2024), attempt to align LLM rewriting with retrieval signals by using reranker scores as feedback. However, these approaches rely on a separate reranking model rather than incorporating direct training signals from dense retrievers. In contrast, our approach introduces a joint training framework that simultaneously optimizes the LLM and the dense retriever, enabling stronger alignment between the two components to conduct a more effective retrieval result.



If you apply for an ITIN online, you can expect to receive it from the IRS within 6 weeks from the date of submission. If you apply in person ......

Instruct$_{q2d}$: Write a passage to answer the query.
Query (q): How long does an itin take ?

D^q: { d_1^q, d_2^q , ... ,d_n^q }

P: {q, d_2^q, d_n^q }

d_2^q **(Chosen Response):** If you apply for an ITIN online, you can expect to receive it from the IRS within 6 weeks from the date of ...

d_n^q **(Rejected Response):** The processing time for an I-130 petition, also known as Affidavit of Support, can vary depending ...

d^q: You can expect to receive itin from the IRS within 6 weeks ......

q D

Instruct$_{q2a}$: You are given a query and a ground truth document. Based on the query, generate a direct and relevant answer ...
Query:How long does an itin take ? / **Ground Truth**:If you qualify...

Answer (y): Apply for itin usually within six weeks.

Similarity	Rank	Score
sim(y, d_1^q)	1	1
sim(y, d_2^q)	3	1/3
...	...	...
sim(y, d_n^q)	n	1/n

Ground Truth (d_*): If you qualify for an ITIN, you will receive a letter from IRS ... within six weeks.

Similarity	Rank	Score
sim(d_*, d_1^q)	5	1/5
sim(d_*, d_2^q)	1	1
...	...	...
sim(d_*, d_n^q)	n	1/n

Sum(SCORE , SCORE) ⇨ $R(d_2^q) > ...... > R(d_1^q) > ......> R(d_n^q)$

Figure 1: Illustration of Our ExpandR Model. ExpandR optimizes both dense retriever and LLM using the LLM-guided contrastive training method and the ranking preference alignment method.

3 ExpandR: An LLM Augmented Dense Retriever Method

As illustrated in Figure 1, this section introduces ExpandR, our LLM-augmented dense retrieval model that leverages query expansions to improve retrieval performance. We begin by describing the overall architecture of ExpandR (Sec. 3.1). We then present how LLM-generated query expansions are used to guide the training of the dense retriever (Sec. 3.2). Finally, we detail a preference-based optimization strategy for the LLM to generate more effective and tailored query expansions (Sec. 3.3).

3.1 Toward a Framework for LLM-Guided Dense Retrieval

This section illustrates how LLMs can be leveraged to enhance dense retrieval. We first introduce the architecture of a standard dense retriever, and then present our proposed method, ExpandR, which incorporates LLM guidance to improve the retrieval model's effectiveness.

Dense Retrieval. Given a query q and a document collection $\mathcal{D} = \{d_1, ..., d_k\}$, dense retrieval models (Karpukhin et al., 2020; Xiong et al., 2021a; Gao and Callan, 2021) first encode the query q and the i-th document d_i into embeddings $\vec{q}$ and $\vec{d_i}$ using PLMs, such as BERT (Devlin et al., 2019):

$$\vec{q} = \text{BERT}_q(q), \quad \vec{d_i} = \text{BERT}_d(d_i). \tag{1}$$

Then the relevance score $S(q, d_i)$ is calculated to estimate the relevance between q and d_i:

$$S(q, d_i) = \text{sim}(\vec{q}, \vec{d_i}), \tag{2}$$

where sim is the dot product operation. Finally, dense retrieval models conduct a KNN search (Douze et al., 2024) to retrieve the top-ranked documents to satisfy the user needs.

ExpandR. Unlike traditional dense retrieval models (Karpukhin et al., 2020), ExpandR leverages the knowledge encoded in LLM to guide dense retrievers via query expansions d^q, aiming to achieve more accurate retrieval results.

Specifically, we first prompt the LLM $\mathcal{M}$ to generate a query expansion d^q as follows:

$$d^q = \mathcal{M}(\text{Instruct}_{\text{q2d}}, q), \tag{3}$$

where $\text{Instruct}_{\text{q2d}}$ denotes an instruction prompting the LLM to generate an informative expansion for the input query (Jagerman et al., 2023). We then model the joint probability of retrieving the ground truth document d_* conditioned on the original query q as:

$$P(d_* \mid q; \Phi, \Theta) = P(d_* \mid q, d^q; \Phi) \cdot P(d^q \mid q; \Theta), \tag{4}$$

where Φ and Θ represent the parameters of the retriever and the LLM, respectively. This formulation can be rewritten as:

$$\begin{aligned} &\log P(d_* \mid q; \Phi, \Theta) = \\ &\log P(d_* \mid q, d^q; \Phi) + \log P(d^q \mid q; \Theta). \end{aligned} \tag{5}$$

Our objective is to jointly optimize the retriever (Φ) and the LLM (Θ) to maximize the above log-likelihood. To enhance training efficiency, we update both components simultaneously using a concurrent strategy (Wang et al., 2024a). The individual optimization details for the retriever and the LLM are presented in Section 3.2 and Section 3.3, respectively. This method allows us to accelerate the overall optimization process while maintaining optimal performance.

3.2 Optimizing Dense Retriever through LLM-Guided Contrastive Training

To maximize $P(d_* \mid q; \Phi, \Theta)$ by optimizing the retriever parameters Φ, we train the dense retriever using both the original query q and its corresponding expansion d^q:

$$\begin{aligned} &\log P(d_* \mid q; \Phi, \Theta) \\ &= \underbrace{\log P(d_* \mid q, d^q; \Phi)}_{\text{Optimize w.r.t. } \Phi} + \underbrace{\log P(d^q \mid q; \Theta)}_{\text{Fixed}}. \end{aligned} \tag{6}$$

To optimize the retriever, we fix Θ and update only Φ by maximizing the retriever-related term:

$$\Phi^* = \arg\max_{\Phi} \log P(d_* \mid q, d^q; \Phi). \tag{7}$$

To incorporate the knowledge of d^q, we simply average the embeddings of both q and d^q as the final query representation $\vec{q}^{\,\text{exp}}$:

$$\vec{q}^{\,\text{exp}} = \frac{\vec{q} + \vec{d}^{\,q}}{2}. \tag{8}$$

Then we treat the expanded query q^{exp} as the new query and compute the similarity score $\text{sim}(q^{\text{exp}}, d)$ between q^{exp} and each candidate document d. The retriever can be contrastively trained using the training loss $\mathcal{L}_{\text{DR}}$:

$$\mathcal{L}_{\text{DR}} = -\log \frac{e^{\text{sim}(q^{\text{exp}}, d_*)}}{e^{\text{sim}(q^{\text{exp}}, d_*)} + \sum_{d_- \in \mathcal{D}^-} e^{\text{sim}(q^{\text{exp}}, d_-)}}, \tag{9}$$

where $\mathcal{D}^-$ represents the set of negative documents, which are sampled from in-batch negatives (Karpukhin et al., 2020).

3.3 Optimizing LLM for Aligning with Ranking Preference

To maximize the probability $P(d_* \mid q; \Phi, \Theta)$, we optimize only the LLM parameters (Θ) while keeping the dense retriever parameters (Φ) fixed.

As shown in Eq. 5, updating Θ alone still affects both terms of the joint probability. Therefore, we optimize Θ as follows:

$$\begin{aligned} \Theta^* = \arg\max_{\Theta} [&\log P(d_* \mid q, d^q; \Phi) \\ &+ \log P(d^q \mid q; \Theta)]. \end{aligned} \tag{10}$$

This objective indicates that a well-generated d^q can not only directly increase the likelihood term $\log P(d^q \mid q; \Theta)$, but also indirectly improve retrieval performance by providing more informative expansions for the term $\log P(d_* \mid q, d^q; \Phi)$. To realize this dual effect, we optimize the LLM parameters through a reward-driven approach. The optimization process involves two steps: first, we define the reward modeling objective (Eq. 10); then, we train the LLM using the Direct Preference Optimization (DPO) method (Amini et al., 2024).

Reward Modeling. We define a reward function $R(d^q)$ to evaluate each candidate expansion $d^q \in \mathcal{D}^q$. The reward combines two complementary signals:

$$R(d^q) = R_{\text{self}}(d^q) + R_{\text{retriever}}(d^q), \tag{11}$$

where $R_{\text{self}}(d^q)$ and $R_{\text{retriever}}(d^q)$ represent the self-reward and the retriever reward, respectively.

Self-Reward. To promote the likelihood term $\log P(d^q \mid q; \Theta)$, we incorporate a self-reward that leverages the LLM's self-consistency. Specifically, we prompt the LLM to generate an answer y according to the query q and the ground-truth document d_*:

$$y = \mathcal{M}(\text{Instruct}_{\text{q2a}}, q, d_*), \tag{12}$$

where $\text{Instruct}_{\text{q2a}}$ guides the LLM to produce an answer y to q. We then treat the answer y as a query and rank the expansion candidates $\mathcal{D}^q$ to compute the self-reward score:

$$R_{\text{self}}(d^q) = \frac{1}{\text{Rank}(y, d^q)}, \tag{13}$$

where $\text{Rank}(y, d^q)$ denotes the rank of document d^q based on its relevance score $\text{sim}(y, d^q)$. A higher rank indicates stronger semantic similarity and consistency between y and d^q.

Retriever Reward. While the self-reward ensures the semantic plausibility of the candidate expansion d^q, it does not necessarily guarantee its usefulness for retrieval, i.e., contributing to $\log P(d_* \mid q, d^q; \Phi)$ (Weller et al., 2024). To address this limitation, we incorporate a retriever reward that captures the preferences of the retriever. Specifically, we compute the Mean Reciprocal Rank (MRR) by treating the ground-truth document d_* as a pseudo-query and ranking the expansion candidates $\mathcal{D}^q$:

$$R_{\text{rank}}(d^q) = \frac{1}{\text{Rank}(d_*, d^q)}, \tag{14}$$

where $\text{Rank}(d_*, d^q)$ denotes the rank of d^q based on the similarity score $\text{sim}(d_*, d^q)$. A higher reward indicates that the expansion is more similar to the ground-truth document, and thus more likely to improve retrieval performance.

LLM Optimization. We fine-tune the LLM $\mathcal{M}$ using preference modeling via DPO. Specifically, we first prompt the LLM to generate a set of expansion candidates $\mathcal{D}^q = \{d_1^q, \ldots, d_k^q\}$ for each query q, by sampling with varying temperature:

$$d^q \sim \mathcal{M}(\text{Instruct}_{\text{q2d}}, q). \tag{15}$$

Then we construct training triples (q, d_+^q, d_-^q) using the reward model $R(\cdot)$ (Eq. 11):

$$R(d_+^q) > R(d_-^q), \tag{16}$$

and follow the DPO method to optimize the LLM ($\mathcal{M}$) using the loss function $\mathcal{L}(\mathcal{M}; \mathcal{M}^{\text{Ref}})$:

$$\begin{aligned} \mathcal{L}(\mathcal{M}; \mathcal{M}^{\text{Ref}}) &= -\mathbb{E}_{(q, d_+^q, d_-^q) \sim \mathcal{P}} \Big[\log \sigma \Big(\\ \beta \log \frac{\mathcal{M}(d_+^q \mid q)}{\mathcal{M}^{\text{Ref}}(d_+^q \mid q)} &- \beta \log \frac{\mathcal{M}(d_-^q \mid q)}{\mathcal{M}^{\text{Ref}}(d_-^q \mid q)} \Big) \Big], \end{aligned} \tag{17}$$

where σ is the sigmoid function, β is a scaling hyperparameter, and $\mathcal{M}^{\text{Ref}}$ is a frozen reference model. The training set $\mathcal{P}$ is composed of preference pairs sampled based on reward scores.

Dataset	**Setting**	**#Query**		
		Train	Dev	Test
E5	LLM	27,000	3,000	-
	Retrieval	637,866	70,874	-
MS MARCO	Retrieval	-	-	6,980
BEIR	Retrieval	-	-	46,379

Table 1: Statistics of the datasets used in our experiments. The E5 dataset is used for joint training of the LLM and the retriever, while MS MARCO and BEIR are used exclusively for evaluation.

4 Experimental Methodology

In this section, we introduce the datasets, evaluation metrics, baselines, and implementation details used in our experiments.

Dataset. We utilize various datasets for training and evaluation. Data statistics are shown in Table 1. More details on data generation and processing are shown in Appendix A.2.

Training. We use the publicly available E5 dataset (Wang et al., 2024b; Springer et al., 2024) to train both the LLMs and dense retrievers. We concentrate on English-based question answering tasks and collect a total of 808,740 queries. From this set, we randomly sample 100,000 queries to construct the DPO data for training LLM, while the remaining queries are used for contrastively training the dense retrieval model. During the construction of DPO preference pairs, we first prompt LLMs to generate documents as query expansions (Wang et al., 2023a). We then filter out queries whose generated documents exhibit low semantic similarity to the original queries. This results in a final dataset comprising 30,000 high-quality queries.

Evaluation. We evaluate retrieval effectiveness using two retrieval benchmarks: MS MARCO (Bajaj et al., 2016) and BEIR (Thakur et al., 2021).

Evaluation Metrics. We use nDCG@10 as the evaluation metric, which is the official evaluation metric of BEIR (Thakur et al., 2021). Statistical significance is tested using a permutation test with $p < 0.05$.

Baselines. We compare our ExpandR model with four representative retrieval models, including BM25 (Robertson et al., 2009), DPR (Karpukhin et al., 2020), CoCondenser (Gao and Callan, 2022), and ANCE (Xiong et al., 2021a).

Then we use different retrievers as backbone models and optimize them using different training strategies. Three encoders as backbone retrievers to

Task	**BM25**	**DPR**	**CoCondenser**	**ANCE**	**BERT**			**Contriever**			**AnchorDR**		
					Raw†	FT$^{\diamond}$	ExpandR	Raw†	FT$^{\diamond}$	ExpandR	Raw†	FT$^{\diamond}$	ExpandR
MS MARCO	22.8	17.7	16.2	37.0	0.29	22.68†	23.54†	20.55	32.96†	33.65†	25.66	36.35†	**37.14**†
Trec-COVID	65.6	33.2	40.4	62.1	3.73	19.72†	19.12†	27.45	30.03†	47.98$^{\dagger\diamond}$	51.44	53.71†	**78.85**$^{\dagger\diamond}$
NFCorpus	32.5	18.9	28.9	23.4	2.60	21.02†	23.98$^{\dagger\diamond}$	31.73	32.33	**34.80**$^{\dagger\diamond}$	31.23	31.04	32.13$^{\diamond}$
NQ	32.9	47.4	17.8	42.9	0.40	15.61†	29.64$^{\dagger\diamond}$	25.37	33.72†	50.39$^{\dagger\diamond}$	26.24	40.30†	**55.91**$^{\dagger\diamond}$
HotpotQA	60.3	39.1	34.0	47.1	0.77	16.10†	29.70$^{\dagger\diamond}$	48.07	58.78†	**70.50**$^{\dagger\diamond}$	52.46$^{\diamond}$	47.84	63.40$^{\dagger\diamond}$
FiQA	23.6	11.2	25.1	29.3	0.59	11.16†	15.40$^{\dagger\diamond}$	24.50	26.06†	32.40$^{\dagger\diamond}$	24.04	28.20†	**34.17**$^{\dagger\diamond}$
ArguAna	31.5	17.5	44.4	40.2	8.19	39.36†	37.57†	37.90	53.48†	**55.39**$^{\dagger\diamond}$	29.50	48.51†	49.16†
Touche-2020	**36.7**	13.1	11.7	23.6	0.39	2.82†	5.89$^{\dagger\diamond}$	16.68$^{\diamond}$	10.46	17.38$^{\diamond}$	12.37	13.76†	24.53$^{\dagger\diamond}$
CQADupStack	29.9	15.3	30.9	28.8	1.10	17.10†	16.47†	28.43	31.60†	33.00$^{\dagger\diamond}$	30.30	34.72†	**35.18**†
Quora	78.9	24.8	82.1	84.7	36.29	77.38†	72.04†	83.50	84.98†	84.67†	83.49	**85.06**†	79.34
DBPedia	31.3	26.3	21.5	26.5	1.57	14.08†	23.05$^{\dagger\diamond}$	29.16	36.46†	**42.32**$^{\dagger\diamond}$	33.58	34.55	40.73$^{\dagger\diamond}$
Scidocs	15.8	7.7	13.6	11.3	0.70	6.04†	9.43$^{\dagger\diamond}$	14.91	14.94	**17.85**$^{\dagger\diamond}$	16.57	15.77	16.82$^{\diamond}$
FEVER	75.3	56.2	61.5	68.1	0.24	36.59†	57.49$^{\dagger\diamond}$	68.20	82.49†	**87.07**$^{\dagger\diamond}$	62.98	77.43†	84.57$^{\dagger\diamond}$
Climate-FEVER	21.4	14.8	16.9	19.8	0.61	11.52†	24.63$^{\dagger\diamond}$	15.50	23.04†	29.77$^{\dagger\diamond}$	23.44	26.63†	**31.76**$^{\dagger\diamond}$
Scifact	66.5	31.8	56.1	50.2	2.81	42.35†	46.27$^{\dagger\diamond}$	64.92	68.84†	**69.68**†	59.84	60.51	63.43$^{\dagger\diamond}$
Avg.BEIR14	43.0	25.5	34.6	39.9	4.29	23.63	29.33	36.88	41.94	48.09	38.39	42.72	**49.28**
Avg.All	41.7	25.0	33.4	39.7	4.02	23.57	28.95	35.79	41.34	47.12	37.54	42.29	**48.47**
Best on	1	0	0	0	0	0	0	0	0	**7**	0	1	6

Table 2: Overall Performance of ExpandR. We follow previous work (Izacard et al., 2021) and report the average performance on 14 BEIR tasks (BEIR14) and all tasks (All). **Bold** and underlined scores indicate the best and second-best results. †, ◇ denote significant improvements over the Raw and FT training settings of each retriever.

examine the generalization ability of our ExpandR, including vanilla BERT (Devlin et al., 2019), Contriever (Izacard et al., 2021), and AnchorDR (Xie et al., 2023). Contriever pretrains PLMs on unlabeled text pairs by encouraging semantically similar sentences to have closer representations in the embedding space. In contrast, AnchorDR leverages the relationships between anchor texts and their linked documents to enhance pretraining. Each retriever is evaluated under three training strategies: (1) **Raw**: directly encoding both queries and documents without fine-tuning; (2) **FT**: standard supervised fine-tuning using query-document triples; and (3) **ExpandR**: it integrates LLM-based query expansion to augment dense retriever and jointly optimizes both LLM and retriever.

Implementation Details. For our query expansion model, we deploy the Meta-LLaMA-3-8B-Instruct (AI@Meta, 2024) as the backbone. The batch size is set to 16, and the learning rate is set to $2e-5$. Optimization is performed using the AdamW optimizer. We employ LoRA (Hu et al., 2022) to efficiently fine-tune the model for 2 epochs. The temperature for the construction of the DPO data varies across $\tau \in \{0.8, 0.9, 1.0, 1.1\}$, with each setting sampled eight times. For the dense retrievers, we utilize three retrievers with different structures: BERT (Devlin et al., 2019), Contriever (Izacard et al., 2021) and AnchorDR (Xie et al., 2023) as the backbone. During training, we set the batch size to 1,024 and the learning rate to $1e-5$, with the model trained for 3 epochs.

5 Evaluation Results

This section presents the overall performance of ExpandR, followed by ablation studies. Then we analyze the semantic distribution of query-document embeddings under different training strategies and evaluate the effectiveness of various reward models. A case study is provided in Appendix A.13.

5.1 Overall Performance

The retrieval performance measured by nDCG@10 across various baselines and training configurations is summarized in Table 2. Additional comparisons with mainstream retriever baselines and extended evaluation results are provided in Appendix A.3 and Appendix A.5, respectively.

As shown in the evaluation results, ExpandR achieves more than 9% improvements over previous retriever models, such as BM25 and ANCE, highlighting its effectiveness. By substituting different retrieval backbone models, ExpandR further demonstrates strong generalization ability, consistently outperforming both zero-shot retrieval (Raw) and standard supervised fine-tuning (FT). Specifically, it achieves an average improvement of 15.6% over Raw and 5.8% over FT across three backbone retrievers on all tasks, validating the benefit of incorporating LLM guidance into dense retrieval.

Notably, ExpandR achieves the best performance on 7 out of 15 tasks when using Contriever, and on 6 tasks with AnchorDR, indicating that its effectiveness holds even with stronger backbone

Model	MARCO	Trec-COVID	NQ	HotpotQA	FiQA	DBPedia	FEVER	Scifact	Avg.
					Contriever				
Query	20.55	27.45	25.37	48.07	24.50	29.16	68.20	64.92	38.53
w/ Retriever Training	32.96	30.03	33.72	58.78	26.06	36.46	82.49	68.84	46.17
ExpandR	**33.65**	47.98	**50.39**	**70.50**	**32.40**	**42.32**	87.07	69.68	**54.25**
w/o LLM Training	33.45	38.64	47.20	66.45	29.74	40.97	85.18	70.55	51.52
w/o Retriever Training	25.20	**59.66**	43.26	65.82	30.12	38.20	82.80	67.74	51.60
w/o Self-Reward	33.05	44.07	47.74	69.62	30.74	42.24	**87.63**	**70.65**	53.21
w/o Retriever Reward	33.47	42.17	49.75	69.12	32.12	40.31	86.52	69.96	52.92
					AnchorDR				
Query	25.66	51.44	26.24	52.46	24.04	33.58	62.98	59.84	42.03
w/ Retriever Training	36.35	53.71	40.30	47.84	28.20	34.55	77.43	60.51	47.36
ExpandR	**37.14**	**78.85**	**55.91**	**63.40**	**34.17**	**40.73**	**84.57**	**63.43**	**57.28**
w/o LLM Training	35.17	70.56	51.24	59.22	29.84	36.11	80.69	61.58	53.05
w/o Retriever Training	29.59	78.50	42.30	57.41	24.91	38.67	79.00	63.40	51.72
w/o Self-Reward	36.56	75.75	54.81	62.74	32.31	40.42	84.41	63.07	56.25
w/o Retriever Reward	37.07	73.75	55.19	61.59	32.97	40.20	82.02	62.47	55.65

Table 3: Ablation Analysis of Key Components in ExpandR on Contriever and AnchorDR. We examine the contributions of LLM training, retriever training, and reward modeling to retrieval performance on 8 important datasets in BEIR. MARCO denotes the MS MARCO dataset.

retrievers. The performance gains are particularly pronounced on challenging datasets such as NQ, HotpotQA, and TREC-COVID, where bridging the semantic gap between queries and documents is more difficult. These results illustrate the capability of ExpandR to mitigate the semantic mismatch in complex retrieval scenarios. Additional results using different LLMs as the backbone for query expansion are provided in Appendix A.6, showing consistent improvements and further validating the robustness of ExpandR across model variants.

5.2 Ablation Study

In this subsection, we conduct comprehensive ablation studies under both Contriever and AnchorDR as backbone retrievers to understand the contribution of each component in ExpandR. We evaluate the impact of different reward modeling methods, LLM optimization strategies, and retriever training.

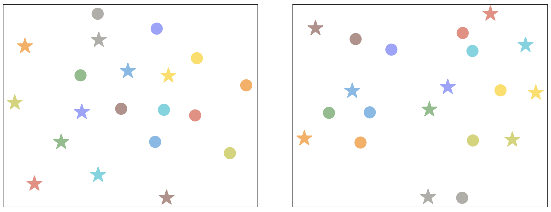
As shown in Table 3, we first include two baselines: "Query" uses raw queries without training, and "w/ Retriever Training" applies contrastive training using raw queries. These settings serve as control groups to isolate the contributions of our LLM optimization and expansion-based retriever training. In both Contriever and AnchorDR backbones, we observe substantial improvements of ExpandR over these baselines, demonstrating that our joint optimization strategy yields significant gains over standard query-only training.

We further assess the role of LLM optimization by removing the DPO training. This results in a 2.73% and 4.23% performance drop on Contriever and AnchorDR, respectively, underscoring the importance of aligning LLM outputs with ranking preferences via preference modeling. Additionally, removing retriever training while retaining LLM optimization significantly impairs performance (2.65 and 5.56 point drops), demonstrating that expansions optimization alone is insufficient unless the retriever is also jointly adapted to leverage them. These findings validate the core motivation of ExpandR that joint optimization of generation and retrieval is key to improving retrieval performance.

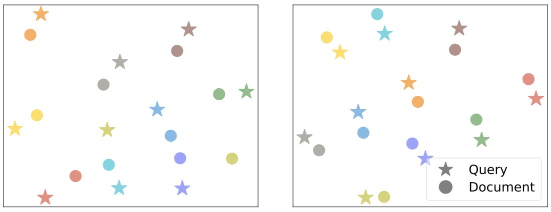
Finally, we conduct ablation studies by individually removing the self-reward and retriever reward to assess the impact of each reward modeling strategy during LLM training. We observe performance degradation in both cases, especially on QA benchmarks such as NQ and HotpotQA, demonstrating their complementary benefits in enhancing generation quality and aligning with retriever preferences. Notably, removing the retriever reward results in a slightly larger drop, indicating that retrieval-guided feedback plays a more crucial role in guiding effective query expansion.

5.3 Visualization of Alignment in the Semantic Embedding Space

We visualize the embeddings of queries and documents using T-SNE to investigate how different



(a) Raw Query.
(b) Vanilla LLM.

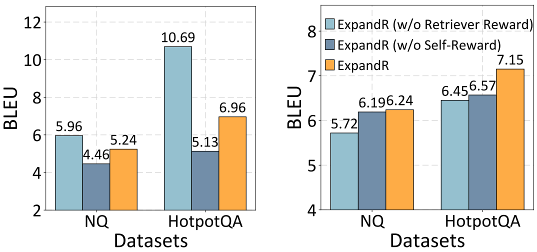


(c) ExpandR (w/o DPO).
(d) ExpandR.

Figure 2: Embedding Visualization of Different Models.

query expansion strategies and retriever configurations affect their semantic alignment. Specifically, we randomly sample 10 query-document pairs and project their embeddings into a two-dimensional space. Each pair is assigned a unique color, with the query represented by a star and the document by a circle, facilitating a direct visual assessment of semantic proximity under various settings. Throughout this analysis, we employ AnchorDR as the base dense retriever to encode queries and documents.

As shown in Figure 2, when using original queries with the base retriever (Figure 2(a)), we observe that query and document embeddings are widely scattered, suggesting a substantial semantic gap between the raw query formulation and its target document. Incorporating expansions generated by a vanilla LLM leads to modest improvements (Figure 2(b)), as some queries shift closer to their corresponding documents. However, the alignment remains inconsistent, and many query-document pairs still appear poorly matched. Fine-tuning the retriever alone results in further improvement (Figure 2(c)), making the embedding space more compact and pulling many expanded queries closer to their paired documents. Nevertheless, the most significant alignment gain is observed when both the query expansion model and the retriever are jointly optimized via preference alignment (Figure 2(d)). In this setting, query-document pairs exhibit significantly tighter and more coherent clustering, suggesting that the combined optimization of the expansion model and the retriever substantially improves semantic consistency and retrieval accuracy. These observations further underscore the importance of jointly aligning both components in dense retrieval systems.



(a) Similarity with Answers. (b) Similarity with Golden Documents.

Figure 3: Effect of Reward Modeling on the Semantic Alignment of Query Expansions.

5.4 Effectiveness of Reward Modeling in Optimizing ExpandR

Figure 3 presents an evaluation of the reward model designed in ExpandR, measured by the text similarity between query expansions and either LLM-generated answers or golden documents. We compare three variants: the full model (ExpandR), w/o Retriever Reward, and w/o Self-Reward.

We first assess the similarity between query expansions and LLM-generated answers (Figure 3(a)). ExpandR w/o Retriever Reward produces expansions most aligned with LLM-generated answers, yielding the highest BLEU score. In contrast, ExpandR w/o Self-Reward achieves the lowest score, indicating that relying solely on the retriever reward is less effective in guiding ExpandR to align with the information in answers, which is particularly important for QA tasks. When the self-reward is incorporated, the BLEU score improves notably, demonstrating its effectiveness in enhancing the factual precision of the expansions.

We then evaluate the similarity between query expansions and ground-truth documents (Figure 3(b)). ExpandR w/o Retriever Reward again performs worst, suggesting that the self-reward alone is insufficient to ensure alignment with golden documents. Conversely, ExpandR w/o Self-Reward performs better, showing the utility of the retriever reward in guiding the model to produce semantically relevant expansions. The full model, integrating both rewards, achieves the highest BLEU score, highlighting the complementary strengths of self-reward and retriever reward in optimizing LLMs to generate high-quality expansions.

6 Conclusion

This paper presents ExpandR, a joint optimization framework that leverages LLM-guided query expansions to enhance retriever training. By jointly training dense retrievers and LLMs, ExpandR improves the effectiveness and compatibility of query expansions within retrieval systems. Experimental results demonstrate that ExpandR consistently boosts performance and offers a new perspective on end-to-end alignment between generative and retrieval components in retrieval pipelines.

Limitations

Despite the effectiveness of ExpandR in improving dense retrieval through LLM-guided query expansions, several limitations remain. First, the quality of expansions is still constrained by the generative capacity of the LLM. If the LLM produces low-quality or biased expansions, the downstream retriever may be misled, even with reward-based supervision. Additionally, although the end-to-end optimization improves alignment between generation and retrieval, it introduces additional computational overhead from both expansion generation and joint training.

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A Appendix

A.1 License

The authors of 4 out of the 15 datasets in the BEIR benchmark (NFCorpus, FiQA-2018, Quora, Climate-Fever) and the authors of ELI5 in the E5 dataset do not report the dataset license in the paper or a repository. We summarize the licenses of the remaining datasets as follows.

MS MARCO (MIT License); FEVER, NQ, and DBPedia (CC BY-SA 3.0 license); ArguAna and Touche-2020 (CC BY 4.0 license); CQADupStack and TriviaQA (Apache License 2.0); SciFact (CC BY-NC 2.0 license); SCIDOCS (GNU General Public License v3.0); HotpotQA and SQuAD (CC BY-SA 4.0 license); TREC-COVID (Dataset License Agreement).

All these licenses and agreements permit the use of their data for academic purposes.

A.2 Additional Experimental Details

This subsection outlines the components of the training data and presents the prompt templates used in the experiments.

Training Datasets. Following the setup of Wang et al. (2024b); Huang et al. (2025a), we use the following datasets: ELI5 (sample ratio 0.1) (Fan et al., 2019), HotpotQA (Yang et al., 2018), FEVER (Thorne et al., 2018), MS MARCO passage ranking (sample ratio 0.5) and document ranking (sample ratio 0.2) (Bajaj et al., 2016), NQ (Karpukhin et al., 2020), SQuAD (Karpukhin et al., 2020), and TriviaQA (Karpukhin et al., 2020). In total, we use 808,740 training examples.

Prompt Templates. Table 4 lists all the prompts used in this paper. In each prompt, "query" refers to the input query for which query expansions are generated, while "Related Document" denotes the ground truth document relevant to the original query. We observe that, in general, the model tends to generate introductory phrases such as "Here is a passage to answer the question:" or "This is the answer to the query:". Before using the model outputs as query expansions or answer signals, we first filter out these introductory phrases to ensure cleaner and more precise expansion results.

A.3 Comparison with Mainstream Retrievers

To further contextualize the performance of ExpandR, we compare it with a range of widely used dense retrievers on the BEIR and MS MARCO datasets, as shown in Table 5. The baselines include RocketQA (Ren et al., 2021), BGE-M3-EN (Chen et al., 2024), TAS-B (Hofstätter et al., 2021), Gen-Q, ColBERT (Khattab et al., 2021), E5 (Wang et al., 2022), WebDRO (Han et al., 2023), and Nomic-Embed (Nussbaum et al., 2024), covering both general-purpose and specialized retrieval models.The base retriever of the ExpandR method is AnchorDR.

Query Expansion
Prompt for Q2D: Please write a passage to answer the question: Question: {} Passage:
Question Answering
Prompt for Q2A: You are given a query and a related document. Based on the query, generate a direct and relevant answer using the information in the document. If the query is a statement, expand on it. If it is a question, provide a direct answer. Avoid any extra description or irrelevant content. Query: {} Related Document: {} Answer:

Table 4: Prompt Templates Used in ExpandR. These prompts are used to generate query expansion results and produce the responses to answer the question.

ExpandR achieves the highest average performance across all datasets (48.5%), consistently outperforming all baselines. Even when excluding MS MARCO—which some retrievers may be specifically optimized for—ExpandR retains its leading position with an average score of 49.3%, suggesting strong generalization across a wide range of domains and task formats.

Among the baselines, E5 and Nomic-Embed stand out as strong retrievers. E5 performs competitively on several QA-style datasets such as MS MARCO and NQ, while Nomic-Embed excels on tasks like ArguAna and HotpotQA. However, both models exhibit noticeable performance drops on other benchmarks—for instance, Nomic-Embed underperforms on MS MARCO and Touche-2020—indicating limitations in generalization. In contrast, ExpandR demonstrates more consistent performance across the board, achieving top-tier results without compromising on robustness. This highlights the robustness and generalizability of our approach across diverse retrieval scenarios.

A.4 Comparison with LLM-Based Query Expansion Methods

In addition to mainstream retrieval baselines, we further compare against representative LLM-based query expansion methods, including

Task	RocketQA	BGE-M3-EN	TAS-B	Gen-Q	ColBERT	E5	WebDRO	Nomic-Embed	ExpandR
MS MARCO	23.2	35.2	40.8	40.8	40.1	**43.1**	40.6	26.4	37.1
Trec-COVID	67.5	44.6	48.1	61.9	67.7	61.7	78.0	67.1	**78.9**
NFCorpus	29.3	32.7	31.9	31.9	30.5	35.1	31.2	**35.5**	32.1
NQ	59.5	29.8	46.3	35.8	52.4	**60.0**	47.2	51.2	55.9
HotpotQA	35.6	68.3	58.4	53.4	59.3	52.4	57.4	**69.1**	63.4
FiQA	30.2	28.3	30.0	30.8	31.7	37.9	28.4	**37.8**	34.2
ArguAna	45.1	**61.5**	42.9	49.3	23.3	51.4	48.0	54.2	49.2
Touche-2020	24.7	13.5	16.2	18.2	20.2	**28.3**	27.6	19.0	24.5
CQADupStack	19.3	**40.2**	31.4	34.7	35.0	28.3	35.2	49.6	35.2
Quora	31.2	**88.7**	83.5	83.0	85.4	87.9	85.8	88.4	79.3
DBPedia	35.6	19.0	38.4	32.8	39.2	33.8	38.1	39.4	**40.7**
Scidocs	16.5	9.6	14.9	14.3	14.5	19.0	15.3	**19.2**	16.8
FEVER	67.6	64.3	70.0	66.9	77.1	58.2	70.9	60.3	**84.6**
C-FEVER	18.0	18.3	22.8	17.5	18.4	15.4	18.9	27.0	**31.8**
Scifact	56.8	71.5	64.3	64.4	67.1	**73.1**	62.2	71.8	63.4
Avg.BEIR14	38.3	42.2	42.8	42.5	44.4	45.9	46.0	49.2	**49.3**
Avg.All	37.3	41.7	42.7	42.4	44.1	45.7	45.6	47.7	**48.5**

Table 5: Performance Comparison of More Mainstream Retriever Baselines on the Beir and MS MARCO Datasets (nDCG@10). The base retriever of the ExpandR method is AnchorDR.

Query2Doc (Wang et al., 2023a), HyDE (Gao et al., 2023), and InteR (Feng et al., 2024), which generate pseudo-documents or hypothetical answers to augment queries but treat these generations as fixed retrieval inputs without adapting the retriever itself. For fairness, we unify the backbone for all methods; specifically, we use LLaMA3-8B-Instruct for the LLMs and AnchorDR for the retriever, and evaluate on 15 BEIR datasets using nDCG@10. Since Quora is a query-to-query matching task where document-style generations are less effective, we also report the average results excluding Quora, denoted as Avg.w/o Quora, to more clearly demonstrate the effectiveness of these query expansion methods.

As shown in Table 6, ExpandR achieves consistently higher performance than the LLM-based query expansion baselines across most datasets. Notably, it improves by 24 and 17 percentage points in nDCG@10 over InteR on ArguAna and FiQA, respectively, and yields a 12% relative gain on the "Avg.w/o Quora" metric, demonstrating consistent benefits across diverse retrieval tasks.

Task	BM25	query2doc	HyDE	InteR	ExpandR
MS MARCO	22.8	14.80	20.48	19.13	**37.14**
Trec-COVID	65.6	66.51	72.02	77.36	**78.85**
NFCorpus	**32.5**	24.09	27.15	25.34	32.13
NQ	32.9	37.21	42.39	44.81	**55.91**
HotpotQA	60.3	46.37	54.16	56.95	**63.40**
FiQA	23.6	15.10	18.40	17.17	**34.17**
ArguAna	31.5	23.78	26.94	24.99	**49.16**
Touche-2020	**36.7**	28.75	30.63	28.10	24.53
CQADupStack	29.9	13.58	18.95	15.21	**35.18**
Quora	78.9	3.11	4.74	3.26	**79.34**
DBPedia	31.30	32.81	35.91	**41.97**	40.73
Scidocs	15.8	11.99	14.80	16.55	**16.82**
FEVER	75.3	77.34	80.71	82.33	**84.57**
C-FEVER	21.4	30.78	31.38	30.03	**31.76**
Scifact	**66.5**	55.83	63.27	65.80	63.43
Avg.w/o Quora	39.01	34.21	38.37	38.98	**46.27**
Avg.All	41.67	32.14	36.13	36.60	**48.47**
Best on	3	0	0	1	**11**

Table 6: Comparison of Retrieval Performance (nDCG@10) Across LLM-based Query Expansion Methods.

A.5 Evaluating Retrieval Completeness through Recall@100

To more comprehensively assess the retrieval capabilities of ExpandR, we report its performance under the Recall@100 metric on both the BEIR and MS MARCO datasets. This metric reflects the model's ability to retrieve a broad set of relevant documents, complementing earlier evaluations based on ranking accuracy. The results are presented in Table 7.

Across all retriever backbones, ExpandR consistently achieves the highest Recall@100 scores, surpassing both the original query (Raw) and supervised retriever (FT) baselines. The improvements are particularly notable on complex multi-hop and fact-seeking datasets such as NQ, HotpotQA, and FEVER, where purely lexical signals are often insufficient for comprehensive retrieval.

These findings suggest that ExpandR not only improves ranking precision but also significantly enhances semantic recall, demonstrating its ability to uncover a wider range of relevant documents. This further validates the robustness and general ap-

Task	BM25	DPR	CoCondenser	ANCE	BERT			Contriever			AnchorDR		
					Raw	FT	ExpandR	Raw	FT	ExpandR	Raw	FT	ExpandR
MS MARCO	65.8	55.2	58.2	83.8	3.32	67.29	69.06	67.19	82.81	83.64	74.95	84.56	**84.83**
Trec-COVID	**49.8**	21.2	7.0	9.6	0.71	2.05	3.30	3.68	3.19	6.58	10.70	10.67	14.44
NFCorpus	25.0	20.8	29.1	22.3	8.66	21.40	25.79	29.41	15.97	**34.07**	28.72	28.93	30.78
NQ	76.0	88.0	67.9	82.2	2.81	65.82	83.23	77.12	88.18	**94.88**	80.42	89.67	94.30
HotpotQA	74.0	59.1	54.7	58.8	5.97	42.57	60.95	70.45	75.64	**87.33**	65.86	66.89	78.72
FiQA	53.9	34.2	60.3	58.2	4.66	39.45	47.52	56.19	61.04	**70.03**	54.89	61.07	65.44
ArguAna	94.2	75.1	93.0	92.3	45.73	95.45	95.38	90.11	98.43	**99.00**	80.65	96.51	96.80
Touche-2020	**53.8**	30.1	27.1	45.2	1.33	14.30	30.37	37.36	31.52	46.35	39.91	38.30	47.00
CQADupStack	60.6	40.3	60.3	57.1	7.05	42.81	42.78	61.40	65.20	**67.39**	62.41	66.44	66.37
Quora	97.3	47.0	98.5	98.6	70.10	96.96	96.06	98.71	**99.09**	93.55	95.71	98.11	96.15
DBPedia	39.8	34.9	34.8	30.8	3.85	25.92	34.69	45.29	48.22	**54.00**	43.94	43.73	48.83
Scidocs	35.6	21.9	34.1	25.2	5.67	22.55	27.28	35.99	37.10	**40.50**	36.99	35.15	36.78
FEVER	93.1	84.0	89.6	91.1	1.91	78.48	88.69	93.56	95.93	**96.94**	93.65	93.09	95.05
C-FEVER	43.6	39.0	37.0	45.6	4.23	44.01	56.84	44.14	58.56	64.56	60.08	60.25	**64.81**
Scifact	90.8	72.7	91.4	81.4	22.39	80.36	81.47	92.60	94.00	**96.00**	90.77	91.43	93.43
Avg.BEIR14	63.4	48.3	56.1	57.0	13.22	48.01	55.31	59.71	62.29	**67.94**	60.34	62.87	66.35
Avg.All	63.6	47.7	56.2	58.8	12.56	49.29	56.23	60.21	63.66	**68.99**	61.31	64.32	67.58
Best on	2	0	0	0	0	0	0	0	1	10	0	0	2

Table 7: Overall Performance of ExpandR on Recall@100.

plicability of our LLM-augmented strategy across diverse retrieval scenarios.

A.6 Robustness under Different LLM Backbones

To examine the robustness of ExpandR across different language model backbones, we replace the LLM used for query expansion with Qwen2.5-7B-Instruct (Yang et al., 2024), a high-quality Chinese-English bilingual model trained with instruction tuning. We keep Contriever as the base retriever. The results are shown in Table 8.

The results show that ExpandR consistently outperforms both the original query baseline (Raw) and the supervised retriever trained with raw queries (FT), achieving the best performance on 14 out of 15 datasets. The performance trend closely mirrors that observed in our original experiments using LLaMA, indicating that the improvements are not tied to a specific LLM architecture. Instead, ExpandR captures a generally effective joint optimization strategy that transfers well across different language models.

Task	Contriever		
	Raw	FT	ExpandR
MS MARCO	20.55	32.96	**33.32**
Trec-COVID	27.45	30.03	**48.18**
NFCorpus	31.73	32.33	**34.58**
NQ	25.37	33.72	**50.86**
HotpotQA	48.07	58.78	**70.04**
FiQA	24.50	26.06	**31.98**
ArguAna	37.90	53.48	**55.15**
Touche-2020	16.68	10.46	**18.09**
CQADupStack	28.43	31.60	**32.95**
Quora	83.50	**84.98**	84.58
DBPedia	29.16	36.46	**41.47**
Scidocs	14.91	14.94	**17.48**
FEVER	68.20	82.49	**87.21**
C-FEVER	15.50	23.04	**30.50**
Scifact	64.92	68.84	**70.00**
Avg.BEIR14	36.88	41.94	**48.08**
Avg.All	35.79	41.34	**47.09**
Best on	0	1	**14**

Table 8: Extended Comparison Results under Qwen2.5-7B-Instruct (nDCG@10). The basic retriever in this experiment is Contriever.

A.7 Evaluation on Stronger Retriever Backbones

In this subsection, we investigate the generalization ability of ExpandR on larger retrievers. Specifically, we additionally evaluate on the recent E5-large-unsupervised model (Wang et al., 2024b), which represents a more advanced dense retriever with enhanced representation capacity.

Table 9 reports results on 15 BEIR datasets under three settings: Raw, FT, and ExpandR applied on top of E5. Across most datasets, ExpandR consistently yields improvements over both Raw and FT variants. In particular, it achieves substantial gains on knowledge-intensive tasks such as TREC-COVID (12.25% over FT) and FEVER (5.18% over FT). On average, ExpandR improves over Raw E5 by 7 percentage points in nDCG@10, and outperforms FT by a clear margin. Moreover, it achieves the best performance on 12 out of 15 datasets, demonstrating stable advantages across diverse retrieval domains. These results confirm that the benefits of our expansion framework are robust and

Task	Raw	FT	ExpandR
MS MARCO	26.15	40.21	**41.33**
Trec-COVID	61.80	64.72	**76.97**
NFCorpus	33.70	35.46	**38.02**
NQ	41.74	50.94	**54.90**
HotpotQA	52.21	56.96	**58.29**
FiQA	43.26	44.20	**44.25**
ArguAna	44.37	47.13	**48.32**
Touche-2020	19.78	19.64	**21.91**
CQADupStack	38.85	41.25	**41.62**
Quora	86.06	**87.70**	87.57
DBPedia	37.10	39.30	**41.46**
Scidocs	**21.88**	20.19	19.84
FEVER	68.59	81.45	**86.63**
C-FEVER	15.73	32.45	**36.04**
Scifact	72.34	**74.55**	74.52
Avg.BEIR14	45.53	49.71	**52.17**
Avg.All	44.24	49.08	**51.44**
Best on	1	2	**12**

Table 9: Retrieval Performance of ExpandR on the E5 Retriever across BEIR Datasets (nDCG@10).

extend to stronger architectures.

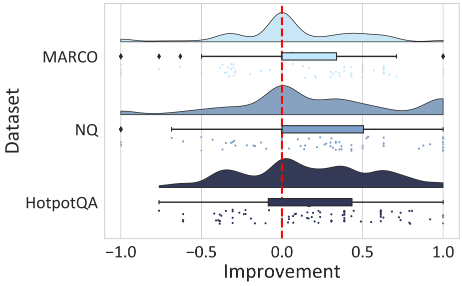
A.8 Generalization to In-Domain and Out-of-Domain Tasks

To examine the robustness of ExpandR under distribution shifts, we partition the BEIR benchmark into in-domain (ID) and out-of-domain (OOD) subsets based on its official taxonomy (Thakur et al., 2021) and whether they overlap with our training data. The ID subset (9/15 tasks) includes MS MARCO, ArguAna, Touche-2020, FEVER, Climate-FEVER, FiQA, NQ, HotpotQA, and DBPedia, all of which overlap with the training corpus of E5. The remaining 6 datasets are treated as OOD, representing unseen domains.

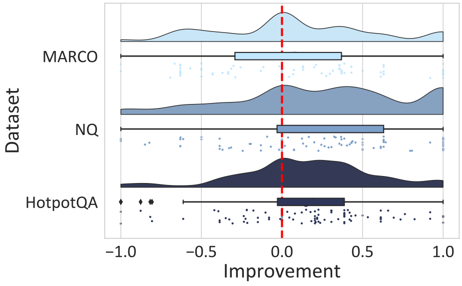
As shown in Table 10, ExpandR consistently outperforms the Raw and FT settings in both ID and OOD scenarios. The gains are larger in the ID subset, with improvements exceeding 5% on several tasks, but remain substantial in the OOD datasets, with average improvements surpassing 3%. These results indicate that the method generalizes robustly across distribution shifts.

A.9 Query Expansion Quality of ExpandR

This section evaluates the quality of query expansion of ExpandR. As shown in Figure 4, we randomly select 100 samples from each dataset to assess the improvement in retrieval performance before and after applying ExpandR.



(a) Unsupervised Dense Retriever.



(b) Supervised Dense Retriever.

Figure 4: Improvements of ExpandR in Both Unsupervised and Supervised Dense Retrievers. We plot the change of nDCG@10 scores before and after the query expansion using our ExpandR model.

Overall, the evaluation results demonstrate that ExpandR consistently improves retrieval performance in both unsupervised (Figure 4(a)) and supervised (Figure 4(b)) settings. However, for the MS MARCO dataset, ExpandR demonstrates limited effectiveness in the supervised setting. This can be attributed to the fact that MS MARCO provides higher-quality training signals, allowing the dense retriever to learn sufficient matching signals from relevance labels. In contrast, ExpandR leads to more substantial performance improvements on the NQ and HotpotQA datasets. This indicates that ExpandR provides essential matching signals for dense retrievers, particularly in retrieval scenarios where high-quality training signals are scarce.

A.10 Effect of Expansion Faithfulness on Retrieval Performance

To examine how the quality of LLM-generated query expansions affects retrieval performance, we conduct a bucket-based analysis (Dechter, 2013) using an LLM-as-judge protocol (Li et al., 2024a). Specifically, GPT-4o is prompted to assign faithfulness scores ranging from 1 to 5 to each expansion, measuring how well it reflects both the original query and its ground-truth document. Queries are

Task	BM25	DPR	CoCondenser	ANCE	BERT			Contriever			AnchorDR		
					Raw	FT	ExpandR	Raw	FT	ExpandR	Raw	FT	ExpandR
Avg.ID	37.31	27.03	27.68	37.17	1.45	18.88	27.43	31.77	39.72	46.54	32.25	39.29	**46.82**
Avg.OOD	48.20	21.95	42.00	43.42	7.87	30.60	31.22	41.82	43.79	48.00	45.48	46.80	**50.96**

Table 10: Average Retrieval Performance on In-Domain and Out-of-Domain Subsets of BEIR using nDCG@10.

then grouped into three categories: hallucinated with scores 1 to 2, moderately faithful with scores 3 to 4, and faithful with a score of 5. We report the average nDCG@10 scores for each bucket across five representative BEIR datasets: HotpotQA, NQ, SciFact, MS MARCO, and NFCorpus.

As shown in Table 11, expansions rated as faithful consistently yield stronger retrieval performance (e.g., 77.55 on HotpotQA), whereas hallucinated expansions exhibit a notable drop (e.g., 51.42 on HotpotQA). Interestingly, in some cases such as HotpotQA and NQ, even hallucinated expansions outperform a retriever fine-tuned trained on raw queries, likely because they introduce implicit cues absent from the original input. These results highlight both the benefits of high-quality expansions and the risks of hallucination, underscoring the importance of faithfulness-aware control mechanisms.

Task	Hallucinated	Moderately Faithful	Faithful
MS Marco	36.79	37.09	37.61
NFCorpus	28.30	48.78	64.87
NQ	47.66	57.47	61.26
HotpotQA	51.42	73.66	77.55
Scifact	55.62	65.90	76.01

Table 11: Performance across Datasets under Different Levels of Expansion Faithfulness.

A.11 Generalization Analysis of Ranking-Aligned LLM Expansions

To examine the generalizability of our ranking-aligned query expansions beyond the retriever used during training, we evaluate ExpandR under two structurally distinct dense retrievers—AnchorDR and BGE-large-1.5—while keeping the reward signals derived from Contriever fixed.

As shown in Table 12, the results show that retrieval using expansions generated by ExpandR consistently yields better performance than using either the original queries or expansions produced by a vanilla LLM, across both retrievers. Although the LLM is optimized using reward signals from Contriever, it achieves strong performance under both AnchorDR and BGE, obtaining the best results on 12 out of 15 datasets in each setting. Notably, even on BGE—an already highly effective retriever—ExpandR still achieves further gains, indicating that the learned expansions do not simply overfit to the behavior of a specific model, but instead capture a transferable ranking preference that generalizes across different retrieval architectures.

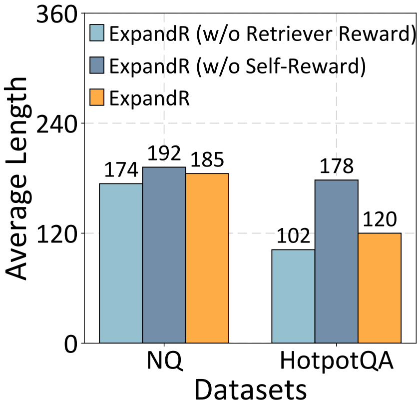


Figure 5: Average Length of Query Expansions Generated by Different Models.

A.12 More Insights into the Self-Reward

While the primary purpose of introducing the self-reward is to enhance the semantic relevance between the generated expansions and the gold answer, we observe that it also serves as an effective regularizer for controlling generation quality. Specifically, we compare the average lengths of the expansions produced by three variants of our model. As shown in Figure 5, removing the self-reward leads to significantly longer generations, which are not necessarily more informative and may introduce hallucinated or off-topic content—a known issue in preference-based tuning methods such as DPO.

With the self-consistency signal in place, the model generates shorter and more focused expansions. To further assess the semantic faithfulness of these generations, we conduct a natural language inference (NLI) based entailment evaluation. As shown in Table 13, although removing the self-

Task	AnchorDR			BGE-large-1.5		
	Query	Vanilla LLM	ExpandR	Query	Vanilla LLM	ExpandR
MS MARCO	25.7	28.9	**29.4**	**42.0**	39.4	40.3
Trec-COVID	51.4	**77.9**	77.1	64.5	77.8	**78.5**
NFCorpus	31.2	31.3	**31.4**	36.8	37.2	**39.3**
NQ	26.2	39.2	**43.0**	51.7	59.6	**60.8**
HotpotQA	52.5	58.0	**59.3**	74.3	75.2	**76.7**
FiQA	24.0	24.9	**25.4**	44.3	44.3	**46.2**
ArguAna	**29.5**	28.0	28.2	**63.5**	61.6	62.6
Touche-2020	12.4	23.5	**25.6**	24.2	25.3	**26.3**
CQADupStack	30.3	31.1	**31.6**	41.7	42.2	**42.6**
Quora	**83.5**	63.2	66.4	**89.0**	87.9	88.0
DBPedia	33.6	38.8	**39.3**	42.1	45.1	**45.2**
Scidocs	16.6	16.9	**17.0**	20.9	22.9	**23.7**
FEVER	63.0	77.5	**79.7**	84.6	86.5	**88.6**
C-FEVER	23.4	29.7	**30.0**	28.4	30.6	**31.7**
Scifact	59.8	62.4	**63.2**	73.5	75.1	**75.3**
Avg.BEIR14	38.4	43.3	**44.1**	52.8	55.1	**56.1**
Avg.All	37.5	42.4	**43.1**	52.1	54.0	**55.1**
Best on	2	1	12	3	0	12

Table 12: Cross-Retriever Evaluation of Ranking-Aligned Expansions (nDCG@10).

Model	NQ		HotpotQA	
	NLI Score	Avg. Length	NLI Score	Avg. Length
Vanilla LLM	6.44	221.76	16.38	129.63
ExpandR (w/o Retriever Reward)	8.12	**174.20**	17.81	**102.60**
ExpandR (w/o Self-Reward)	6.65	192.76	13.75	178.29
ExpandR	**8.64**	185.11	**18.67**	120.52

Table 13: Comparison of NLI Entailment Scores and Average Lengths of Extensions Generated by Different Models.

reward increases the average length, it results in lower entailment scores, suggesting reduced semantic alignment with the gold answer. In contrast, the full model—trained with both the retriever-based and self-rewards—achieves the highest entailment scores while keeping the generation length moderate, indicating a better balance between informativeness and faithfulness.

These results suggest that the self-reward not only enhances $\log P(d^q \mid q; \Theta)$, but also implicitly constrains the LLM from over-generating, thereby mitigating hallucination and improving the overall quality of the query expansions during DPO training.

A.13 Case Study

To further demonstrate the effectiveness of ExpandR, we conduct a case study by randomly sampling a query from the evaluation dataset. We then compare retrieval performance using the raw queries, expanded queries by vanilla LLM, and expanded queries by ExpandR.

As shown in Table 14, query expansion significantly improves retrieval effectiveness over using the raw query, with both LLM-generated variants achieving higher nDCG@10. While the vanilla LLM introduces relevant terms such as “temperature” and “humidity”, its expansions are often verbose and include redundant or inconsistent content (e.g., conflicting temperature ranges). This reflects a lack of alignment between generation and retrieval utility.

In contrast, ExpandR produces expansions that are more concise and semantically aligned with the golden passage, incorporating key concepts such as “human behavior”, “environmental factors”, and “virus transmission”. These expansions better match the relevance signals favored by the retriever, leading to improved ranking performance. This example illustrates how preference-guided fine-tuning in ExpandR enables the LLM to generate expansions that are both informative and behaviorally aligned with the retrieval model.

Query: How does the coronavirus respond to changes in the weather?
Golden Pagssage: Epidemics ... occur during the winter months. ... Two major contributing factors are the changes in environmental parameters and human behavior. Studies have revealed the effect of temperature and humidity on respiratory virus stability and transmission rates. More recent research highlights the importance of the environmental factors, especially temperature and humidity ...

Raw Query

nDCG@10: 22.01%
Original Query: How does the coronavirus respond to changes in the weather?

Vanilla LLM

nDCG@10: 76.63%
Expanded Query: The coronavirus, like many other viruses, has been observed to respond to changes in the weather by experiencing fluctuations in transmission and spread. ... the virus tends to thrive in environments with high humidity, typically above 40%, and a temperature range of 37°C to 46°C. ... studies have found that the virus can survive on surfaces for longer periods at lower temperatures and humidity levels, ...

ExpandR

nDCG@10: 100.00%
Expanded Query: The coronavirus responds to changes in the weather by adapting its transmission and spread patterns. This is because temperature, humidity, and other environmental factors can affect the stability and survival of the virus on surfaces, ... research suggests that the virus may thrive in cooler and more humid environments, ... such as air circulation, ventilation, and human behavior.

Table 14: Case Study. All experiments are conducted based on the Contriever model under the zero-shot setting. To facilitate evaluation, we highlight the potential matching phrases between the golden passage and both the original and expanded queries. Different colors are used to annotate these matched phrases for each method: Green for Direct Retrieval, Red for Vanilla LLM, and Blue for ExpandR.