PREDICTING DRUG-LIKENESS VIA BIOMEDICAL KNOWLEDGE ALIGNMENT AND EM-LIKE ONE-CLASS BOUNDARY OPTIMIZATION

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ABSTRACT

The advent of generative AI now enables large-scale *de novo* design of molecules, but identifying viable drug candidates among them remains an open problem. Existing drug-likeness prediction methods often rely on ambiguous negative sets or purely structural features, limiting their ability to accurately classify drugs from non-drugs. In this work, we introduce BOUNDR.E: a novel modeling of drug-likeness as a compact space surrounding approved drugs through a dynamic deep one-class boundary approach. Specifically, we enrich the chemical space through biomedical knowledge alignment, and then iteratively tighten the drug-like boundary by pushing non-drug-like compounds outside via an Expectation-Maximization (EM)-like process. Empirically, BOUNDR.E achieves 10% F1-score improvement over the previous state-of-the-art and demonstrates robust cross-dataset performance, including zero-shot toxic compound filtering. Additionally, we showcase its effectiveness through comprehensive case studies in large-scale *in silico* screening. Our codes and constructed benchmark data under various schemes are provided at: github.com/eugenebang/boundr_e.

1 INTRODUCTION

The expansion of deep generative models have reshaped the drug discovery landscape by rapidly producing vast libraries of *de novo* compounds (Guan et al., 2023; Lee et al., 2023; Song et al., 2024), conditioned by desired activity or pocket structure. However, evaluating which of these molecules are truly "drug-like" is yet an open problem. Traditional property-based metrics, such as Rule of five (Lipinski et al., 1997), offer efficient preliminary screening but lack a definitive criterion to separate truly viable drug candidates from non-drugs. Thus, a data-driven approach for precisely defining drug-likeness in terms of chemical or compound space is now required.

Fundamentally, the approval of drugs depends on more than just structural validity. A candidate must exhibit favorable physicochemical properties and align with relevant biomedical context, including biological target interactions, pharmacogenetic association and disease pathway modulation. Yet, most existing predictive models ignore these requirements, depending heavily on structural features alone (Zhu et al., 2023). Further complicating this structural reliance, approved drugs are highly scattered in the chemical space, with fewer than two drugs typically sharing the same core scaffold. This dispersion makes it challenging to define a compact decision boundary of drugs without including non-drugs on a structural representation space, as observed in our initial studies (Appendix B). Specifically, **defining such a boundary poses two major challenges:** 1) the absence of definitive negatives, as any molecule could potentially be drug-like, and 2) the vast scale of chemical space, estimated to be up to 10^{60} compounds (Polishchuk et al., 2013), making it impractical to sample a representative set for training.

Dues to these challenges, supervised approaches that treat non-drug molecules as "hard negatives" tend to over-restrict the boundary (Sun et al., 2022), while purely unsupervised methods often become too broad (Li et al., 2024). Positive-unlabeled (PU) learning methods (Lee et al., 2022) also as-

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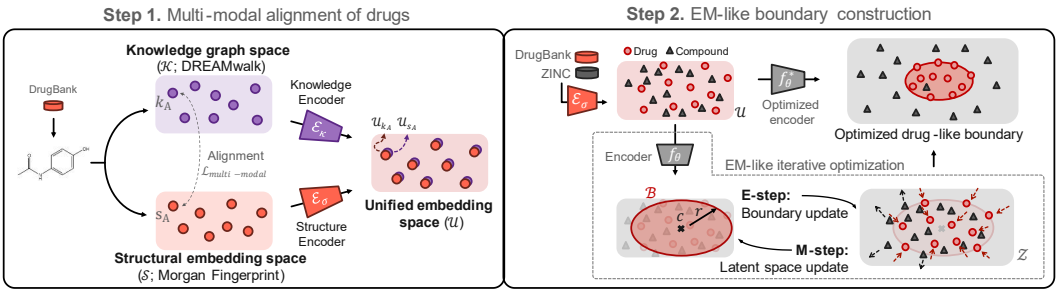


Figure 1: Overview of BOUNDR.E. **Step 1** performs multi-modal mixup of two drug spaces: knowledge graph $\mathcal{K}$ and molecular fingerprint $\mathcal{S}$ spaces into a unified space $\mathcal{U}$. **Step 2** performs EM-like boundary optimization, where in E-step boundary $\mathcal{B}$ is updated and in M-step the latent space $\mathcal{Z}$ is updated by pushing the out-boundary non-drugs further while contracts drugs to the center.

sume a well-defined negative distribution, which is impractical for the unbounded compound space, where defining its representative set is challenging (Appendix A.6). Traditional one-class classifiers (Schölkopf et al., 2001; Tax & Duin, 2004; Ruff et al., 2018), though independent of negative samples, remain unused in drug-likeness prediction due to their static nature and overly broad boundaries which leads to high false positives.

In response, we propose BOUNDR.E: a novel approach that frames drug-likeness prediction as consrtucting a deep one-class boundary within a biomedical knowledge-integrated embedding space. A desirable drug-likeness space should form a tight boundary around approved drugs, including only a small fraction of existing compounds as drug candidates. BOUNDR.E achieves this by iteratively refining the boundary through an Expectation-Maximization (EM)-like process, adaptively enclosing drug-like molecules while pushing non-drug-like compounds outward. Furthermore, we integrate the essential biomedical context via multi-modal mixup, merging molecular structure representation with biomedical knowledge graphs into a unified embedding space to address the structural reliance.

Through extensive experiments, we show that our approach yields notable improvements in drug-likeness prediction task of up to 10% F1-score improvement over the previous state-of-the-art, with robust performance across time-based splits, scaffold-based splits, and cross-dataset validation on three benchmark sets. Additionally, BOUNDR.E excels in zero-shot toxic compound filtering, with comprehensive case studies further showcasing its utility in large-scale screening of AI-generated compounds.

Our key contributions include: 1) Novel formulation of drug-likeness prediction as a one-class classification without reliance on negatives. 2) Proposal of deep EM-like optimization of both the drug-likeness boundary and the embedding space for accurate drug-likeness prediction. 3) Knowledge-integrated multi-modal alignment of structure and biomedical knowledge embeddings for defining drug-likeness via machine learning. These advances collectively establish BOUNDDR.E as a dynamic, data-driven tool for initial screens of generated molecules, pushing the frontiers of drug-likeness prediction and improving the overall efficiency and reliability of AI-driven drug discovery.

2 DEEP DRUG-LIKE BOUNDARY OPTIMIZATION

Given the highly dispersed nature of drugs in the chemical space and their approval based on both structure and biomedical knowledge, our framework combines these two modalities into a unified space, followed by iterative refinement of a hyperspherical one-class boundary to capture drug-like compounds (Figure 1). The alignment of the two modalities (Section 2.2) and the boundary optimization (Section 2.3) are the keys to addressing the challenges posed by an unbounded chemical space and the absence of explicit negatives.

2.1 PROBLEM DEFINITION

We propose a new perspective on the problem of drug-likeness prediction as constructing a compact and adaptive one-class boundary $\mathcal{B}$ around drug-like compounds in a theoretically unbounded chemical space (Figure 2). Let this space of all compounds be denoted as $\mathcal{X}_{\text{comp}}$, with subset $\mathcal{X}_{\text{drug}} \subset \mathcal{X}_{\text{comp}}$ representing drug-like compounds. The approved drug dataset $\mathcal{D}_{\text{drug}}$ represents a subset of the $\mathcal{X}_{\text{drug}}$, while compound dataset $\mathcal{D}_{\text{comp}}$ is a biased subset of $\mathcal{X}_{\text{comp}}$, where its small yet unknown portion

are potential drugs that are to be rescued (Appendix A.6). As visualized in Figure 2, existing non-drug datasets $\mathcal{D}_{\text{comp}}$ (e.g. ZINC, PubChem, ChEMBL) form a distinct distribution and can not be a representative set of the compound space (Appendix C.5).

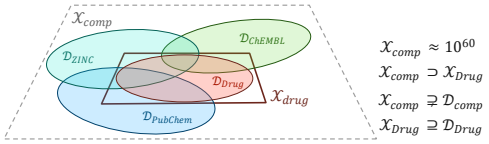


Figure 2: Problem definition of drug-likeness prediction with compound spaces $\mathcal{X}$ and datasets $\mathcal{D}$.

We define the drug-likeness boundary through 1) training encoders $\mathcal{E}_\kappa$ and $\mathcal{E}_\sigma$ for alignment of drugs' knowledge space $\mathcal{K}$ and structural space $\mathcal{S}$ into a unified embedding space $\mathcal{U}$, followed by 2) EM-like iterative optimization of boundary $\mathcal{B}_{c,r}$ and its latent space $\mathcal{Z}_\theta$. Notations throughout this paper are organized in Appendix D.

2.2 Knowledge-integrated Multi-modal Alignment

Each *drug* can be represented by two complementary embeddings, which encode different aspects of drug-likeness: molecular structure and biomedical context. Drugs are enriched with their annotations of target proteins, pharmacogenetic associations and pathway modulation, which can be represented through knowledge graph embeddings. The primary challenge is to train a structural encoder that can also position *non-drugs*, which lack biomedical information, within a biologically enriched space. Our objective is to unify these two embeddings into a common latent space $\mathcal{U}$, ensuring alignment and consistency between structural and knowledge-based representations of drugs.

To achieve this, we introduce a *knowledge-integrated multi-modal mixup* strategy. This involves softening the CLIP loss (Radford et al., 2021) to encourage alignment between the two embedding spaces based on semantic drug similarities as prior knowledge. The alignment is further augmented with geodesic mixup (Oh et al., 2024), which ensures that the interpolated samples lie on a geodesic path between the embeddings. By employing this strategy, we create a unified embedding space that leverages the contexts from both molecular structure and biomedical knowledge, capturing a richer representation of drug-like properties.

We begin by aligning two key embedding spaces of biomedical knowledge graph embeddings $\boldsymbol{k}_{\text{drug}} \in \mathcal{K}$ (Bang et al., 2023) and molecular structural embeddings $\boldsymbol{s}_{\text{drug}} \in \mathcal{S}$ (Morgan Fingerprint). This integration is crucial as it enriches drug representations by combining molecular structures with their biomedical contexts. We train two encoders: a knowledge encoder $\mathcal{E}_\kappa : \mathcal{K} \to \mathcal{U}$ and a structural encoder $\mathcal{E}_\sigma : \mathcal{S} \to \mathcal{U}$, where both map their respective embeddings to a unified latent space $\mathcal{U} \subset \mathbb{R}^d$. The details of the aligned spaces are explained in Appendix C.2.

2.2.1 Softened CLIP Loss with ATC Similarity

In this section, we propose a novel knowledge-integration strategy for multi-modal contrastive learning of drug representations. We soften the CLIP loss (Radford et al., 2021) by incorporating semantic similarity (Jiang & Conrath, 1997) between drugs using Anatomic Therapeutic Chemical (ATC) classification. For a batch of data $D = \{(\boldsymbol{s}_i, \boldsymbol{k}_i)\}_{i=1}^M$, the original CLIP loss is given by:

$$C(\boldsymbol{s}, \boldsymbol{k}) = \frac{1}{M} \sum_{i=1}^{M} -\log \frac{\exp(\boldsymbol{s}_i \odot \boldsymbol{k}_i / \tau)}{\sum_{j=1}^{M} \exp(\boldsymbol{s}_i \odot \boldsymbol{k}_j / \tau)} \qquad \mathcal{L}_{\text{CLIP}} = \frac{1}{2}(C(\boldsymbol{s}, \boldsymbol{k}) + C(\boldsymbol{k}, \boldsymbol{s})) \tag{1}$$

where $C(\boldsymbol{s}, \boldsymbol{k})$ is the contrastive loss for structural and knowledge embeddings, $\boldsymbol{s}_i \odot \boldsymbol{k}_i = \mathcal{E}_\sigma(\boldsymbol{s}) \cdot \mathcal{E}_\kappa(\boldsymbol{k})^T$ represents their dot-product similarity, and τ is the scaling temperature factor.

To introduce prior knowledge of drug similarities, we incorporate an ATC code similarity matrix $W_{\text{ATC}} = [w_{i,j}]$, where $w_{i,j} \in [0, 1]$ measures the semantic similarity between drugs i and j. The modified loss incorporating W_{ATC} becomes a weighted sum over the soft labels (Eq. 3):

$$C_{\text{soft}}(\boldsymbol{s}, \boldsymbol{k}, W_{\text{ATC}}) = \frac{1}{M} \sum_{i=1}^{M} \sum_{j=1}^{M} w_{i,j} \left(-\log \frac{\exp(\boldsymbol{s}_i \odot \boldsymbol{k}_j / \tau)}{\sum_{l=1}^{M} \exp(\boldsymbol{s}_i \odot \boldsymbol{k}_l / \tau)} \right) \tag{2}$$

$$\mathcal{L}_{\text{softCLIP}} = \frac{1}{2}(C_{\text{soft}}(\boldsymbol{s}, \boldsymbol{k}, W_{\text{ATC}}) + C_{\text{soft}}(\boldsymbol{k}, \boldsymbol{s}, W_{\text{ATC}})) \tag{3}$$

Here, instead of assuming a hard one-hot target where $w_{i,i} = 1$ and $w_{i,j} = 0$ for $i \neq j$ (as of the original CLIP loss), the soft labels $w_{i,j}$ encourage similarity of drug pair embeddings to match their semantic similarity. Details of ATC similarity computation are provided in Appendix C.3.

2.2.2 GEODESIC MIXUP FOR EMBEDDING ALIGNMENT

Several studies have reported the problem of "modality gap" in contrastive learning frameworks including CLIP (Wang & Isola, 2020; Liang et al., 2022). To further improve alignment of the two domains, we apply geodesic mixup (Oh et al., 2024) to interpolate between embeddings on a hypersphere, ensuring the points are aligned uniformly in the latent space. Given two points $\vec{a}$ and $\vec{b}$, the mixup is performed along the geodesic path:

$$m_\lambda(\vec{a}, \vec{b}) = \vec{a}\frac{\sin(\lambda\vartheta)}{\sin(\vartheta)} + \vec{b}\frac{\sin((1-\lambda)\vartheta)}{\sin(\vartheta)}$$

where $\vartheta = \cos^{-1}(\vec{a} \cdot \vec{b})$, and $\lambda \sim \text{Beta}(\alpha, \alpha)$. Within the batch of length M, geodesic mixup interpolates information from data indices i and $i' = M - i$ with λ and $1 - \lambda$ fraction, respectively. This allows smooth interpolation between data pairs, improving consistency within the latent space.

With our formulation, we introduce three forms of mixup (visualized in Figure 8):

Structural Mix (S-Mix) Interpolates within the structural embedding space ($m_\lambda(\boldsymbol{s}_i, \boldsymbol{s}_{i'})$):

$$C_S(\boldsymbol{s}, \boldsymbol{k}) = \frac{1}{M}\sum_{i=1}^{M} -\lambda \log \frac{\exp(m_\lambda(\boldsymbol{s}_i, \boldsymbol{s}_{i'}) \odot \boldsymbol{k}_i/\tau)}{\sum_{j=1}^{M}\exp(\boldsymbol{s}_i \odot \boldsymbol{k}_j/\tau)} - (1-\lambda)\log\frac{\exp(m_\lambda(\boldsymbol{s}_i, \boldsymbol{s}_{i'}) \odot \boldsymbol{k}_{i'}/\tau)}{\sum_{j=1}^{M}\exp(\boldsymbol{s}_i \odot \boldsymbol{k}_j/\tau)}$$

$$\mathcal{L}_{S\text{-Mix}} = \frac{1}{2}(C_S(\boldsymbol{s}, \boldsymbol{k}) + C_S(\boldsymbol{k}, \boldsymbol{s})) \tag{4}$$

Knowledge Mix (K-Mix) Interpolates within the knowledge graph embedding space and has the same formula with S-Mix, except that it is applied to knowledge embedding-side ($m_\lambda(\boldsymbol{k}_i, \boldsymbol{k}_{i'})$):

$$\mathcal{L}_{K\text{-Mix}} = \frac{1}{2}(C_K(\boldsymbol{s}, \boldsymbol{k}) + C_K(\boldsymbol{k}, \boldsymbol{s})) \tag{5}$$

Knowledge-Structural Mix (KS-Mix) Interpolates the knowledge and structural embeddings simultaneously:

$$C_{KS}(\boldsymbol{s}, \boldsymbol{k}) = \frac{1}{M}\sum_{i=1}^{M} -\log\frac{\exp(m_\lambda(\boldsymbol{s}_i, \boldsymbol{s}_{i'}) \odot m_\lambda(\boldsymbol{k}_i, \boldsymbol{k}_{i'})/\tau)}{\sum_{j=1}^{M}\exp(\boldsymbol{s}_i \odot \boldsymbol{k}_j/\tau)}$$

$$\mathcal{L}_{KS\text{-Mix}} = \frac{1}{2}(C_{KS}(\boldsymbol{s}, \boldsymbol{k}) + C_{KS}(\boldsymbol{k}, \boldsymbol{s})) \tag{6}$$

These interpolations ensure the robustness of embedding space by smoothing the transitions between similar drugs and ensuring embeddings respect the L2-norm constraint of the hypersphere.

The final multi-modal alignment loss is a weighted sum:

$$\mathcal{L}_{\text{multi-modal}} = \lambda_{\text{softCLIP}}\mathcal{L}_{\text{softCLIP}} + \mathcal{L}_{S\text{-Mix}} + \mathcal{L}_{K\text{-Mix}} + \mathcal{L}_{KS\text{-Mix}} \tag{7}$$

We optimize the parameters of encoders $\mathcal{E}_\sigma$ and $\mathcal{E}_\kappa$ using the Adam optimizer (Kingma, 2014). The trained structure encoder $\mathcal{E}_\sigma$ is further utilized to project the chemical structural features into the unified embedding space $\mathcal{U}$ for downstream tasks including the drug-likeness boundary generation.

2.3 EM-LIKE ITERATIVE OPTIMIZATION OF DRUG-LIKENESS BOUNDARY

Once the multi-modal embeddings are aligned into the unified space $\mathcal{U}$, we define a hyperspherical boundary $\mathcal{B}$ in a latent space $\mathcal{Z}$, which is generated by an encoder $f_\theta : \mathcal{U} \to \mathcal{Z}$. This boundary is characterized by its center $\boldsymbol{c}$ and radius r, and the goal is to optimize $\mathcal{B}$ such that it encapsulates as many drug-like compounds as possible while minimizing the inclusion of non-drug-like compounds, leading to decreased in-boundary compound ratio ρ.

We formulate the optimization of this drug-likenss boundary $\mathcal{B}$ as an iterative process inspired by the Expectation-Maximization (EM) algorithm. The model adjusts the boundary parameters (a hypersphere with center $\boldsymbol{c} \in \mathbb{R}^d$ and radius r) in the Expectation (E)-step, while refining the embedding space $\mathcal{Z}$ and its encoder f_θ during the Maximization (M)-step. This allows the boundary to evolve throughout training, with each iteration improving the its compactness and reducing the false-positive rate. The full algorithm is provided in Appendix A.1.

2.3.1 EXPECTATION STEP: BOUNDARY UPDATE

In the E-step, we update $\boldsymbol{c}$ and r to enclose $\alpha \approx 100\%$ of drug-like compounds, keeping the embedding function f_θ fixed. Given the set of embedded drug compounds $\boldsymbol{z}_{\text{drug}} = \{f(\boldsymbol{x}; \theta^{(t)}) : \boldsymbol{x} \in \mathcal{X}_{\text{drug}}\}$ at iteration time step t, the boundary parameters are updated as follows:

$$\boldsymbol{c}^{(t+1)} = \frac{1}{|\boldsymbol{z}_{\text{drug}}|} \sum_{\boldsymbol{z} \in \boldsymbol{z}_{\text{drug}}} \boldsymbol{z}, \quad r^{(t+1)} = Q^{\alpha}_{\boldsymbol{z} \in \boldsymbol{z}_{\text{drug}}} \left(\|\boldsymbol{z} - \boldsymbol{c}^{(t+1)}\|_2 \right), \quad r^{(t+1)}_{\text{comp}} = \max_{\boldsymbol{z} \in \boldsymbol{z}_{\text{comp}}} \left(\|\boldsymbol{z} - \boldsymbol{c}^{(t+1)}\|_2 \right),$$

Here, $\boldsymbol{c}^{(t+1)}$ is the center of the drug-like compounds at iteration $t+1$, $r^{(t+1)}$ is the radius of the smallest hypersphere containing the user-given $\alpha \approx 100\%$ of drug-like compounds, defined by the α-th percentile (Q^{α}) of the set of distances $\|\boldsymbol{z} - \boldsymbol{c}^{(t+1)}\|_2$. $r^{(t+1)}_{\text{comp}}$ captures the boundary of all compounds. Compounds located outside the drug-like boundary are treated as pseudo-negatives in the next M-step:

$$\mathcal{X}_{\text{out}} := \{\boldsymbol{x} \in \mathcal{X}_{\text{comp}} \mid d^{(t)}(\boldsymbol{x}; \theta, \boldsymbol{c}) > r^{(t+1)}\},$$

where $d^{(t)}(\boldsymbol{x}; \theta, \boldsymbol{c}) = \|f(\boldsymbol{x}; \theta^{(t)}) - \boldsymbol{c}^{(t+1)}\|_2$ is the Euclidean distance from the boundary center.

2.3.2 MAXIMIZATION STEP: EMBEDDING FUNCTION UPDATE

In the M-step, we optimize the embedding function $f_\theta : \mathcal{U} \to \mathcal{Z}$ with parameters θ to reduce the inclusion of non-drug-like compounds inside the boundary while keeping drug-like compounds near the center. The total loss function consists of two metric terms:

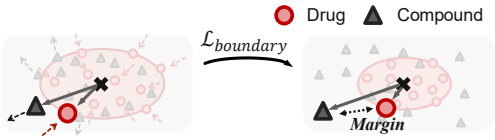


Figure 3: Latent space optimization during M-step. The margin between drug and compound are increased.

1. **Drug loss** $\mathcal{L}_{\text{drug}}$, which encourages drugs to be located closer the center of the boundary:
$$\mathcal{L}_{\text{drug}}(\theta) = \textstyle\sum_{\boldsymbol{x} \in \mathcal{X}_{\text{drug}}} d_t(\boldsymbol{x}; \theta, \boldsymbol{c})$$
2. **Out-boundary loss** $\mathcal{L}_{\text{out}}$, which pushes non-drugs labeled as pseudo-negatives during the E-step to the compound space boundary:
$$\mathcal{L}_{\text{out}}(\theta) = \textstyle\sum_{\boldsymbol{x} \in \mathcal{X}_{\text{out}}} \max\left(r^{(t+1)}_{\text{comp}} - d_t(\boldsymbol{x}; \theta, \boldsymbol{c}), 0\right)$$

The loss terms can be interpreted as reducing/increasing the samples' distances $d(\boldsymbol{x})$ to 0 and $r^{(t+1)}_{\text{comp}}$ for drugs and out-boundary compounds, respectively. We then combine the two loss terms to yield a total loss described as:

$$\mathcal{L}_{\text{boundary}}(\theta) = \mathcal{L}_{\text{drug}}(\theta) + \lambda_{\text{out}} \cdot \mathcal{L}_{\text{out}}(\theta) \tag{8}$$

where λ_{out} controls the strength of the out-boundary penalty. This loss iteratively improves the separation between drug-like and non-drug-like compounds, increasing the margin $\sum_{\boldsymbol{x}_{\text{drug}} \in \mathcal{X}_{\text{drug}}} \sum_{\boldsymbol{x}_{\text{comp}} \in \mathcal{X}_{\text{comp}}} d(\boldsymbol{x}_{\text{comp}}) - d(\boldsymbol{x}_{\text{drug}})$ between drugs and compounds (Figure 3).

We show that minimizing the metric loss function (Eq. 8) leads to a boundary $\mathcal{B}$ that encapsulates drug-like compounds while excluding non-drug-like ones, improving drug-likeness prediction accuracy:

Theorem 1 (Reduction of in-boundary non-drugs). *Optimizing a neural network encoder with the distance-based loss function reduces the number of non-drugs inside the boundary $|\mathcal{X}_{\text{in-boundary}}|$ between two successive steps $t_1 < t_2$, where $\mathcal{L}^{(t_1)}_{drug} > \mathcal{L}^{(t_2)}_{drug}$ and $\mathcal{L}^{(t_1)}_{out} > \mathcal{L}^{(t_2)}_{out}$.*

The proof is provided in Appendix A.2.

Finally, convergence is determined by the in-boundary compound ratio $\rho_t = |\mathcal{X}^{(t)}_{\text{in-boundary}}|/|\mathcal{X}_{\text{comp}}|$. The algorithm stops when the change in ρ_t between iterations is smaller than a threshold ϵ: $|\rho_{t+1} - \rho_t| < \epsilon$ for n_{patience} consecutive iterations. The computational complexity analysis of each step is provided in Appendix A.4, demonstrating linearity with respect to the number of samples and data dimensionality. In addition, a multi-initialization technique applied to avoid the EM-like models' sensitivity to initialization, is further detailed in Appendix A.5.

Overall, our EM-like framework iteratively refines the boundary and embedding space, resulting in a compact boundary that effectively excludes non-drug-like compounds. The knowledge-aligned embeddings of $\mathcal{U}$ further enhances the model's drug-likeness prediction capabilities.

Table 1: Drug-like compound identification performance with time-split setting. Mean and standard deviation of 10 fold CV are provided. Best performance and its comparable results (paired t-test $p < 0.05$) are marked in bold, and second-best are underlined. (Avg: Average)

	F1 (↑)	IDR (↑)	ICR (↓)	AUROC (↑)	Avg. Precision (↑)
FP-SVM (Boser et al., 1992)	0.665 (0.0126)	0.823 (0.0111)	0.067 (0.0052)	0.963 (0.0021)	0.724 (0.0174)
FP-XGB (Chen & Guestrin, 2016)	0.692 (0.0141)	0.815 (0.0205)	0.055 (0.0048)	0.966 (0.0026)	0.775 (0.0213)
FP-OCSVM (Schölkopf et al., 2001)	0.090 (0.0025)	0.274 (0.0000)	0.489 (0.0101)	0.331 (0.0030)	0.148 (0.0022)
FP-DeepSVDD (Ruff et al., 2018)	0.166 (0.0087)	0.834 (0.0350)	0.840 (0.0381)	0.494 (0.0532)	0.097 (0.0157)
FP-nnPU (Kiryo et al., 2017)	0.608 (0.0239)	0.789 (0.0367)	0.083 (0.0081)	0.944 (0.0049)	0.706 (0.0261)
FP-PU with NN (Li & Liu, 2003)	0.634 (0.0224)	0.791 (0.0296)	0.072 (0.0079)	0.949 (0.0045)	0.720 (0.0214)
DrugMetric (Li et al., 2024)*	0.170 (0.0319)	0.767 (0.1271)	0.760 (0.2028)	*N/A*	*N/A*
D-GCAN (Sun et al., 2022)	0.669 (0.1770)	**0.942 (0.0337)**	0.160 (0.2808)	0.918 (0.1396)	0.613 (0.1874)
DeepDL (Lee et al., 2022)	0.740 (0.0584)	0.888 (0.0546)	0.054 (0.0225)	**0.979 (0.0114)**	0.886 (0.0374)
BOUNDR.E	**0.846 (0.0165)**	0.799 (0.0184)	**0.009 (0.0031)**	0.978 (0.0029)	**0.908 (0.0096)**

*DrugMetric's GMM classifier fails to provide prediction probabilities for AUROC and Average Precision calculation

3 EXPERIMENTS

3.1 SETUP

Dataset Approved drugs are sourced from DrugBank v5.1.12 (Knox et al., 2024) and removed all withdrawn drugs. 100k non-drug compounds are sampled from ZINC20 (Irwin et al., 2020), limited to clean, annotated entries. We evaluate our model on drug-likeness prediction under two split scenarios: *scaffold*-based and *time*-based. The scaffold-based split ensures the molecular scaffolds in train, validation, and test sets are mutually exclusive, based on the Bemis-Murcko scaffolds (Bemis & Murcko, 1996). This evaluation scheme is applied to measure the models' generalizablilty when an unseen scaffold compound is input (Appendix C.4.1). In the time-based split, drugs are partitioned based on their approval year (e.g., drugs approved post-2011 are in the test set), to reflect the temporal evolution of approved drug properties (Appendix C.4.2).

Baselines We compare our model to established drug-likeness prediction models: DeepDL (Lee et al., 2022), D-GCAN (Sun et al., 2022), and DrugMetric (Li et al., 2024), as well as several general machine learning classifiers: SVM (Boser et al., 1992), XGBoost (Chen & Guestrin, 2016), Naive PU algorithm by Li & Liu (2003) implemented with neural network, nnPU (Kiryo et al., 2017), OC-SVM (Schölkopf et al., 2001), and DeepSVDD (Ruff et al., 2018). Each general baseline is provided with molecular fingerprints as input features. Implementation details are provided in Appendix C.7.

3.2 DRUG-LIKENESS PREDICTION PERFORMANCES

We evaluate performance of models in distinguishing approved drugs from ZINC compounds under both split strategies—time-based split and scaffold-based split. We report the results using F1-score and two metrics: In-boundary Drug Ratio (IDR) and In-boundary Compound Ratio (ICR):

$$\text{IDR} = \frac{|\text{Drugs in boundary}|}{|\text{Total drugs in test set}|} = \text{TPR}, \quad \text{ICR} = \frac{|\text{Compounds in boundary}|}{|\text{Total compounds in test set}|} = \text{FPR}.$$

IDR, equivalent of True Positive Rate (TPR), reflects how well the boundary captures drug-like compounds, while ICR, representing False Positive Rate (FPR), measures how well non-drug compounds are excluded. Reported AUROC further measures the models' capabilities in balancing the trade-off between TPR and FPR. In addition, Average Precision (AP), Recall@k and Precision@k evaluates the quality of recommended compounds (Appendix E.1).

As a result, our model consistently outperforms binary classifiers, PU learners, and one-class classification models across both split settings. For the time-based split (Table 1), our model achieves the highest F1, AUROC, and AP, demonstrating its ability to adapt to unseen drug-like compounds. Results for the scaffold-based split (Appendix E.2) further confirm the robustness of our approach, highlighting its capacity to generalize across diverse molecular structures.

Ablation studies Ablation studies on both the multi-modal alignment with softened CLIP loss (Table 2) and EM-like boundary optimization (Table 3) further confirm the complementary nature of BOUNDR.E's two modules in improving drug-likeness prediction. The full ablation study results including each component of Mixup and other traditional classifiers are provided in Appendix E.5.

Table 2: Drug-like compound identification with EM-like boundary optimization on embedding space aligned with different alignment methods. Best and its comparable results (paired t-test $p < 0.05$) are marked in bold.

Alignment method	F1 (↑)	ICR (↓)
No Alignment (only FP)	0.54 (0.032)	0.057 (0.0161)
Manifold Alignment	0.40 (0.045)	**0.009 (0.0055)**
CLIP	0.59 (0.022)	0.025 (0.0133)
Geodesic Mixup	0.69 (0.045)	0.025 (0.0133)
Ours - softCLIP	0.73 (0.037)	**0.018 (0.0066)**
Ours	**0.83 (0.049)**	**0.012 (0.0086)**

Table 3: Drug-like compound identification with different classifiers on knowledge-aligned space. Best and its comparable results (paired t-test $p < 0.05$) are marked in bold.

Aligned space	F1 (↑)	ICR (↓)
+ MLP	0.77 (0.020)	0.046 (0.0053)
+ SVM	**0.86 (0.012)**	0.050 (0.0050)
+ XGB	0.75 (0.012)	0.019 (0.0023)
+ naive PU	0.82 (0.011)	0.031 (0.0029)
+ DeepSVDD	0.32 (0.079)	0.351 (0.1148)
+ Ours − EM	0.44 (0.162)	0.259 (0.1931)
+ Ours	0.83 (0.049)	**0.012 (0.0086)**

Cross-dataset evaluation We further tested generalizability through cross-compound dataset evaluation. Models are first trained on PubChem or ChEMBL compound sets then tested with the ZINC compounds, with the drug set (DrugBank) and its split setting fixed. As a result, binary classifiers and PU-learning frameworks show heavy decline in performances whereas one-class classifers show no effect. BounDr.E demonstrate only moderate decline in both scaffold-based and time-based splits (Appendix E.3). This result shows the generalizability of our one-class boundary approach by not relying on the non-drug set. Experimental details are available in Appendix C.5.

3.3 Zero-shot Toxic compound identification

To test our model's capacity to filter out potentially toxic compounds, we performed a zero-shot evaluation on toxic compound sets including DrugBank's withdrawn drug list and organ-toxicity groups (hepatotoxic, cardiotoxic, and carcinogenic compounds, Wu et al. (2023)).

Table 4: False-positive rate of toxic compound groups. Lowest and its comparable results (paired t-test $p < 0.05$) are marked in bold.

	Withdrawn	Hepatotoxic	Cardiotoxic	Carcinogenic
FP-XGB	0.96 (0.003)	0.96 (0.003)	0.85 (0.010)	0.93 (0.010)
FP-OCSVM	0.69 (0.002)	**0.53 (0.003)**	0.25 (0.006)	0.86 (0.001)
FP-nnPU	0.95 (0.009)	0.94 (0.007)	0.87 (0.028)	0.86 (0.017)
DrugMetric*	*N/A*	0.77 (0.073)	0.76 (0.118)	0.82 (0.087)
DGCAN	0.91 (0.020)	0.85 (0.023)	0.88 (0.045)	0.95 (0.017)
DeepDL	0.91 (0.016)	0.92 (0.018)	0.85 (0.042)	0.84 (0.025)
BounDr.E	**0.51 (0.014)**	0.54 (0.009)	**0.20 (0.009)**	**0.19 (0.014)**

*DrugMetric fails to infer scaffolds not present in approved drug and ZINC datasets

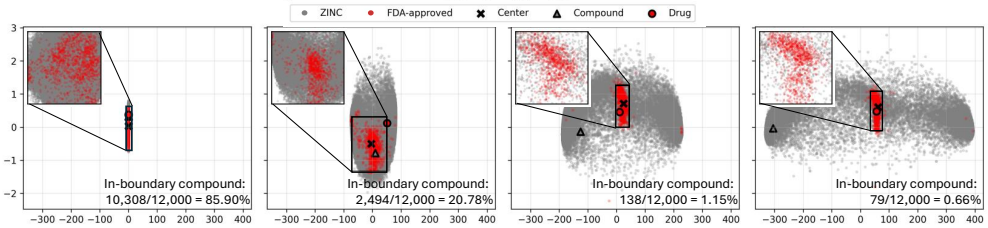
As shown in Table 4, our model demonstrates lower false-positive rate compared to baseline models, consistently identifying toxic compounds from diverse categories as out of drug boundary. Furthermore, error analysis on the withdrawn drugs reveal that among the 51% false-positive, most of them are withdrawn from some regions yet approved in others (Appendix E.4.2). These results indicates that our boundary, along with its integrated biomedical contexts, can effectively generalize to toxic compounds, offering a promising tool for early-stage toxicity filtering. Full table of baseline model performances are provided in Appendix E.4.

3.4 Embedding space visualization

Figure 4 displays the evolution of our embedding space as the EM-like boundary optimization proceeds. It is easy to spot that the compounds from ZINC database are being pushed out of the boundary as FDA-approved drugs form more compact space as training epochs increase. The zoomed-in boxes of each epoch further visualizes how the density of ZINC-compounds decreases as the embedding space is optimized. This visualization effectively demonstrates our model's ability to iteratively refine the embedding space, making it increasingly more drug-focused over time.

3.5 Application of BounDr.E in Drug Discovery Pipelines

To validate the effectiveness of BounDr.E in drug discovery pipelines, we analyzed the drug-likeness scores for six compound sets spanning different stages of drug discovery: AI-generated compounds (TargetDiff (Guan et al., 2023) and MOOD (Lee et al., 2023)), investigational compounds and world-approved drugs (ZINC20 (Irwin et al., 2020)), withdrawn drugs, and FDA-approved drugs. Figure 5 shows a clear progression, with compounds moving closer to the center of the drug boundary as they advance through the drug development pipeline. The result reflects



(a) Epoch 0 (b) Epoch 33 (c) Epoch 66 (d) Epoch 99

Figure 4: PCA visualization of latent space at each epoch of boundary optimization. Box on the upper-left corner displays the space within the drug-like boundary based on PC1 and PC2. Red circle and gray triangle display the movement of drug and zinc compound samples respectively, as training proceeds.

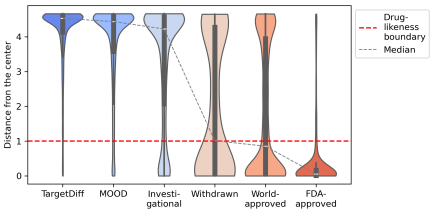


Figure 5: Distribution of drug-like scores of compounds in different drug discovery stages.

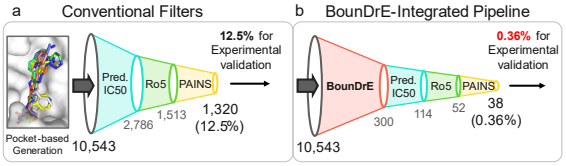


Figure 6: Integration of BOUNDR.E for filtering 10,543 BCR-ABL pocket-based generated compounds

the increasing likelihood of drug-likeness as a compound matures from AI-generated candidates to approved drugs.

Lastly, we demonstrate the utility of our model for initial screening and its potential real-world impact in target-based drug discovery pipeline (Figure 6). Utilizing three well-known anti-cancer targets, BCR-ABL, EGFR and CDK6, we first generated 10k anti-cancer compounds with pocket-aware generative model (Guan et al., 2023). Then, we compared the filtering capability of our approach with property-based filters, detailed in Appendix E.6.1. As a result, while BOUNDR.E-integrated pipeline yields a very practical number (38 out of 10,543) for wet lab validations, the filtered compound list exhibited enhanced drug-like properties including Quantitative Estimate of Drug-likeness (QED) and Synthetic Accessibility (SA) scores (Appendix E.6.2).

This ability to rank and filter candidates based on accurate drug-likeness measure provides a valuable tool for *in silico* screening, accelerating early-stage compound prioritization.

4 CONCLUSION AND FUTURE WORKS

In this work, we introduced BOUNDR.E, a novel framework for drug-likeness prediction that combines knowledge-aligned embeddings with EM-like one-class boundary optimization. By leveraging structural and biomedical knowledge through application of softened CLIP loss and Geodesic Mixup, BOUNDR.E creates a robust multi-modal embedding space. Our experiments show that BOUNDR.E consistently outperforms state-of-the-art models, excelling at identifying drug-like compounds while effectively filtering out toxic molecules, with case studies demonstrating its utility as initial screen of drug candidates.

Several opportunities for improvement remain in our framework. The EM-like strategy still requires solid approaches and theoretical support for reaching global optima, and lower reliance to initialization points. Further experimental validation of the screened compounds, including efficacy, toxicity and PK/PD profiles, may provide more convincing results on the utility data-driven drug filters in drug discovery endeavours. In particular, the applicability of our model to specific therapeutic area can be further elaborated. Nonetheless, we believe our model is a promising complementary solution for prioritizing drug-like compounds in early-stage development for efficiency in drug discovery.

REFERENCES

Timothy L. Bailey and Charles Elkan. Unsupervised learning of multiple motifs in biopolymers using expectation maximization. *Mach. Learn.*, 21(1–2):51–80, Oct 1995. ISSN 0885-6125. doi:

10.1007/BF00993379. URL https://doi.org/10.1007/BF00993379.

Dongmin Bang, Sangsoo Lim, Sangseon Lee, and Sun Kim. Biomedical knowledge graph learning for drug repurposing by extending guilt-by-association to multiple layers. *Nature Communications*, 14(1):3570, 2023.

Guy W Bemis and Mark A Murcko. The properties of known drugs. 1. molecular frameworks. *Journal of medicinal chemistry*, 39(15):2887–2893, 1996.

Bernhard E Boser, Isabelle M Guyon, and Vladimir N Vapnik. A training algorithm for optimal margin classifiers. In *Proceedings of the fifth annual workshop on Computational learning theory*, pp. 144–152, 1992.

Tianqi Chen and Carlos Guestrin. Xgboost: A scalable tree boosting system. In *Proceedings of the 22nd acm sigkdd international conference on knowledge discovery and data mining*, pp. 785–794, 2016.

David A DeGoey, Hui-Ju Chen, Philip B Cox, and Michael D Wendt. Beyond the rule of 5: lessons learned from abbvie's drugs and compound collection: miniperspective. *Journal of medicinal chemistry*, 61(7):2636–2651, 2017.

Jiaqi Guan, Wesley Wei Qian, Xingang Peng, Yufeng Su, Jian Peng, and Jianzhu Ma. 3d equivariant diffusion for target-aware molecule generation and affinity prediction. In *The Eleventh International Conference on Learning Representations*, 2023. URL https://openreview.net/forum?id=kJqXEPXMsE0.

Jihun Ham, Daniel Lee, and Lawrence Saul. Semisupervised alignment of manifolds. In *International Workshop on Artificial Intelligence and Statistics*, pp. 120–127. PMLR, 2005.

John J Irwin, Khanh G Tang, Jennifer Young, Chinzorig Dandarchuluun, Benjamin R Wong, Munkhzul Khurelbaatar, Yurii S Moroz, John Mayfield, and Roger A Sayle. Zinc20—a free ultralarge-scale chemical database for ligand discovery. *Journal of chemical information and modeling*, 60(12):6065–6073, 2020.

Jay J Jiang and David W Conrath. Semantic similarity based on corpus statistics and lexical taxonomy. In *Proceedings of the 10th Research on Computational Linguistics International Conference*, pp. 19–33, 1997.

Wengong Jin, Regina Barzilay, and Tommi Jaakkola. Junction tree variational autoencoder for molecular graph generation. In *International conference on machine learning*, pp. 2323–2332. PMLR, 2018.

Diederik P Kingma. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*, 2014.

Ryuichi Kiryo, Gang Niu, Marthinus C Du Plessis, and Masashi Sugiyama. Positive-unlabeled learning with non-negative risk estimator. *Advances in neural information processing systems*, 30, 2017.

Craig Knox, Mike Wilson, Christen M Klinger, Mark Franklin, Eponine Oler, Alex Wilson, Allison Pon, Jordan Cox, Na Eun Chin, Seth A Strawbridge, et al. Drugbank 6.0: the drugbank knowledgebase for 2024. *Nucleic acids research*, 52(D1):D1265–D1275, 2024.

Kyunghoon Lee, Jinho Jang, Seonghwan Seo, Jaechang Lim, and Woo Youn Kim. Drug-likeness scoring based on unsupervised learning. *Chemical Science*, 13(2):554–565, 2022.

Seul Lee, Jaehyeong Jo, and Sung Ju Hwang. Exploring chemical space with score-based out-of-distribution generation. In *International Conference on Machine Learning*, pp. 18872–18892. PMLR, 2023.

Bowen Li, Zhen Wang, Ziqi Liu, Yanxin Tao, Chulin Sha, Min He, and Xiaolin Li. Drugmetric: quantitative drug-likeness scoring based on chemical space distance. *Briefings in Bioinformatics*, 25(4), 2024.

Xiaoli Li and Bing Liu. Learning to classify texts using positive and unlabeled data. In *IJCAI*, volume 3, pp. 587–592. Citeseer, 2003.

Victor Weixin Liang, Yuhui Zhang, Yongchan Kwon, Serena Yeung, and James Y Zou. Mind the gap: Understanding the modality gap in multi-modal contrastive representation learning. *Advances in Neural Information Processing Systems*, 35:17612–17625, 2022.

Christopher A Lipinski, Franco Lombardo, Beryl W Dominy, and Paul J Feeney. Experimental and computational approaches to estimate solubility and permeability in drug discovery and development settings. *Advanced drug delivery reviews*, 23(1-3):3–25, 1997.

Shengchao Liu, Hanchen Wang, Weiyang Liu, Joan Lasenby, Hongyu Guo, and Jian Tang. Pre-training molecular graph representation with 3d geometry. In *International Conference on Learning Representations*, 2022. URL https://openreview.net/forum?id=xQUe1pOKPam.

Changdae Oh, Junhyuk So, Hoyoon Byun, YongTaek Lim, Minchul Shin, Jong-June Jeon, and Kyungwoo Song. Geodesic multi-modal mixup for robust fine-tuning. *Advances in Neural Information Processing Systems*, 36, 2024.

Pavel G Polishchuk, Timur I Madzhidov, and Alexandre Varnek. Estimation of the size of drug-like chemical space based on gdb-17 data. *Journal of computer-aided molecular design*, 27:675–679, 2013.

Alec Radford, Jong Wook Kim, Chris Hallacy, Aditya Ramesh, Gabriel Goh, Sandhini Agarwal, Girish Sastry, Amanda Askell, Pamela Mishkin, Jack Clark, et al. Learning transferable visual models from natural language supervision. In *International conference on machine learning*, pp. 8748–8763. PMLR, 2021.

Lukas Ruff, Robert Vandermeulen, Nico Goernitz, Lucas Deecke, Shoaib Ahmed Siddiqui, Alexander Binder, Emmanuel Müller, and Marius Kloft. Deep one-class classification. In *Proceedings of the 35th International Conference on Machine Learning*, volume 80, pp. 4393–4402. PMLR, 10–15 Jul 2018. URL https://proceedings.mlr.press/v80/ruff18a.html.

Camilo Ruiz, Marinka Zitnik, and Jure Leskovec. Identification of disease treatment mechanisms through the multiscale interactome. *Nature communications*, 12(1):1796, 2021.

Bernhard Schölkopf, John C Platt, John Shawe-Taylor, Alex J Smola, and Robert C Williamson. Estimating the support of a high-dimensional distribution. *Neural computation*, 13(7):1443–1471, 2001.

Yuxuan Song, Jingjing Gong, Minkai Xu, Ziyao Cao, Yanyan Lan, Stefano Ermon, Hao Zhou, and Wei-Ying Ma. Equivariant flow matching with hybrid probability transport for 3d molecule generation. *Advances in Neural Information Processing Systems*, 36, 2024.

Sven Stegemann, Chris Moreton, Sami Svanbäck, Karl Box, Geneviève Motte, and Amrit Paudel. Trends in oral small-molecule drug discovery and product development based on product launches before and after the rule of five. *Drug Discovery Today*, 28(2):103344, 2023.

Jinyu Sun, Ming Wen, Huabei Wang, Yuezhe Ruan, Qiong Yang, Xiao Kang, Hailiang Zhang, Zhimin Zhang, and Hongmei Lu. Prediction of drug-likeness using graph convolutional attention network. *Bioinformatics*, 38(23):5262–5269, 2022.

David MJ Tax and Robert PW Duin. Support vector data description. *Machine learning*, 54:45–66, 2004.

Ava M Vargason, Aaron C Anselmo, and Samir Mitragotri. The evolution of commercial drug delivery technologies. *Nature biomedical engineering*, 5(9):951–967, 2021.

Tongzhou Wang and Phillip Isola. Understanding contrastive representation learning through alignment and uniformity on the hypersphere. In *International conference on machine learning*, pp. 9929–9939. PMLR, 2020.

Lianlian Wu, Bowei Yan, Junshan Han, Ruijiang Li, Jian Xiao, Song He, and Xiaochen Bo. Toxric: a comprehensive database of toxicological data and benchmarks. *Nucleic Acids Research*, 51 (D1):D1432–D1445, 2023.

Wenyu Zhu, Yanxing Wang, Yan Niu, Liangren Zhang, and Zhenming Liu. Current trends and challenges in drug-likeness prediction: Are they generalizable and interpretable? *Health Data Science*, 3:0098, 2023.

A DETAILS IN EM-LIKE BOUNDARY OPTIMIZATION

A.1 ALGORITHM OF EM-LIKE BOUNDARY OPTIMIZATION

Algorithm 1 EM-like Training for Drug Boundary Optimization

Require: Dataset $\mathcal{X} = \{\boldsymbol{x}_i\}_{i=1}^N = \mathcal{X}_{\text{drug}} + \mathcal{X}_{\text{comp}}$, Learning rate η_θ , Convergence tolerance ϵ
Ensure: Optimized embedding space parameters θ^* and boundary parameters $\boldsymbol{c}^*, r^*$

Initialize neural network parameters $\theta^{(0)}$, boundary parameters $c^{(0)}$, $r^{(0)}$
$\mathcal{X} \leftarrow \mathcal{E}_\sigma(\mathcal{X})$ where $\mathcal{E}_\sigma$ is pretrained multi-modal structure encoder
$\rho^{(0)} = \frac{|\mathcal{X}^{(0)}_{\text{in-boundary}}|}{|\mathcal{X}_{\text{comp}}|}$ where $\mathcal{X}^{(0)}_{\text{in-boundary}} := \left\{\boldsymbol{x} \mid \|f(\boldsymbol{x}_{\text{comp}}; \theta^{(0)}) - \boldsymbol{c}^{(0)}\|_2 \leq r^{(0)}\right\}$
Set $t = 0$
while $|\rho_{t+1} - \rho_t| \geq \epsilon$ **do**
  E-step (Boundary update):
    $\boldsymbol{z}_{\text{drug}} \leftarrow f(\boldsymbol{x}_{\text{drug}}; \theta^{(t)})$
    $\boldsymbol{c}^{(t+1)} \leftarrow \frac{1}{|\boldsymbol{z}_{\text{drug}}|} \sum \boldsymbol{z}_{\text{drug}}$
    $r^{(t+1)} \leftarrow \max\left(\|\boldsymbol{z}_{\text{drug}} - \boldsymbol{c}^{(t+1)}\|_2\right)$, $r^{(t+1)}_{\text{comp}} \leftarrow \max\left(\|z_{\text{comp}} - \boldsymbol{c}^{(t+1)}\|_2\right)$
    Identify $\mathcal{X}_{\text{out}}$
  M-step (Embedding function update):
    $\mathcal{L}_{\text{boundary}}(\theta^{(t)}) \leftarrow \mathcal{L}_{\text{drug}}(\theta^{(t)}, \boldsymbol{c}^{(t+1)}, r^{(t+1)}) + \lambda_{\text{out}} \cdot \mathcal{L}_{\text{out}}(\theta^{(t)}, \boldsymbol{c}^{(t+1)}, r^{(t+1)})$
    $\theta^{(t+1)} \leftarrow \theta^{(t)} - \eta_\theta \cdot \text{Adam}\left(\nabla_\theta \mathcal{L}(\theta^{(t)}, \boldsymbol{c}^{(t+1)}, r^{(t+1)})\right)$
    $\rho^{(t+1)} \leftarrow \frac{|\mathcal{X}^{(t)}_{\text{in-boundary}}|}{|\mathcal{X}_{\text{comp}}|}$ where $\mathcal{X}^{(t)}_{\text{in-boundary}} := \left\{\boldsymbol{x} \mid \|f(\boldsymbol{x}_{\text{comp}}; \theta^{(t+1)}) - \boldsymbol{c}^{(t+1)}\|_2 \leq r^{(t+1)}\right\}$
  Increment $t \leftarrow t + 1$
end while
Return Optimized parameters $\theta^*, \boldsymbol{c}^*, r^*$

A.2 PROOF OF THEOREM 1

To recap, the M-step of the EM-like iterative optimizes the latent space with the following loss terms:

$$\mathcal{L}_{\text{drug}}(\theta) = \sum_{\boldsymbol{x} \in \mathcal{X}_{\text{drug}}} d_t(\boldsymbol{x}; \theta, \boldsymbol{c}) \tag{9}$$

$$\mathcal{L}_{\text{out}}(\theta) = \sum_{\boldsymbol{x} \in \mathcal{X}_{\text{out}}} \max\left(r^{(t+1)}_{\text{comp}} - d_t(\boldsymbol{x}; \theta, \boldsymbol{c}), 0\right) \tag{10}$$

$$\mathcal{L}_{\text{boundary}}(\theta) = \mathcal{L}_{\text{drug}}(\theta) + \lambda_{\text{out}} \cdot \mathcal{L}_{\text{out}}(\theta) \tag{11}$$

where $d_t(\boldsymbol{x}; \theta, \boldsymbol{c}) = \|f(\boldsymbol{x}; \theta^{(t)}) - \boldsymbol{c}^{(t+1)}\|_2$ is the Euclidean distance of samples from the drug center, and λ_{out} is a hyperparameter controlling the strength of the out-boundary penalty. The loss terms can be interpreted as reducing/increasing the samples' distances $d(x)$ to 0 and $r^{(t+1)}_{\text{comp}}$ for drugs and out-boundary compounds, respectively.

Theorem 1 (Reduction of In-boundary Non-drugs). *Optimizing a neural network encoder with Euclidean distance loss to regress distance of non-drugs toward a radius of r_{comp} and drugs toward 0 leads to a decrease in the number of non-drugs in boundary $|\mathcal{X}_{in\text{-}boundary}|$ between two successive time steps $t_1 < t_2$ where $\mathcal{L}^{(t_1)}_{drug} > \mathcal{L}^{(t_2)}_{drug}$ and $\mathcal{L}^{(t_1)}_{out} > \mathcal{L}^{(t_2)}_{out}$.*

To prove this, we will break down the proof to show that the decreasing nature of r and the inconsistency that arises if the number of points inside an arbitrary threshold ν increases during the optimization of the Euclidean distance-based loss.

Proposition 1 (Shrinkage of r): *As the optimization of the Euclidean distance loss proceeds over time, the drug boundary radius r, defined as the maximum distance of drug-like points from the center $\boldsymbol{c}$, decreases.*

Proof: Let $\mathcal{X}_{\text{drug}} \subset \mathbb{R}^d$ denote the set of drug-like compounds and $\boldsymbol{c} \in \mathbb{R}^d$ be a center point. The drug loss function $\mathcal{L}_{\text{drug}}$ (Eq. 9) is given by:

$$\mathcal{L}_{\text{drug}} = \sum_{\boldsymbol{x} \in \mathcal{X}_{\text{drug}}} d(\boldsymbol{x}) = \sum_{\boldsymbol{x} \in \mathcal{X}_{\text{drug}}} \|f(\boldsymbol{x}; \theta) - \boldsymbol{c}\|_2,$$

where $d(\boldsymbol{x})$ represents the Euclidean distance between point $f(\boldsymbol{x}; \theta)$ and $\boldsymbol{c}$.

The objective of the optimization process is to minimize $\mathcal{X}_{\text{drug}}$ by penalizing larger distances more severely with the square operation, while attracting points further away from $\boldsymbol{c}$ more strongly, and since the Euclidean distance norm is a strictly convex function, any reductions in the loss $\mathcal{X}_{\text{drug}}$ implies a reduction in the distance $\|f(\boldsymbol{x}; \theta) - \boldsymbol{c}\|_2$ for each $\boldsymbol{x} \in \mathcal{X}_{\text{drug}}$.

Thus the furthest point $\boldsymbol{x}* \in \mathcal{X}_{\text{drug}}$, which determines r, experiences a decrease in distance from $\boldsymbol{c}$ as the loss function decreases, and therefore, as $\mathcal{L}_{\text{drug}}$ is minimized, r decreases as the optimization progresses. □

Lemma 1 (Impact of Compounds Inside ν to $\mathcal{L}_{\text{out}}$): *The contribution to the out-boundary loss $\mathcal{L}_{out}$ from points $\boldsymbol{x}$ with $d(\boldsymbol{x}) < \nu$ is greater than the contribution from points with $d(\boldsymbol{x}) \geq \nu$.*

Proof: The out-boundary loss $\mathcal{L}_{\text{out}}$ (Eq. 10) is given by:

$$\mathcal{L}_{\text{out}}(\theta) = \sum_{\boldsymbol{x} \in \mathcal{X}_{\text{out}}} \max\left(r_{\text{comp}} - d(\boldsymbol{x}), 0\right),$$

where $d(\boldsymbol{x})$ represents the Euclidean distance between the compound $\boldsymbol{x}$ and the center $\boldsymbol{c}$. Considering the loss contribution of a point $\boldsymbol{x} \in \mathcal{X}_{\text{out}}$ with distance $d(\boldsymbol{x})$, the individual contribution to the loss for this point is

$$\mathcal{L}_{\text{out},\boldsymbol{x}} = \max\left(r_{\text{comp}} - d(\boldsymbol{x}), 0\right).$$

So, for points $\boldsymbol{x}$ such that $\boldsymbol{x}$ with $d(\boldsymbol{x}) < \nu$ with given an arbitrary threshold radius, we have

$$r_{\text{comp}} - d(\boldsymbol{x}) > r_{\text{comp}} - \nu.$$

On the other hand, for points where $d(\boldsymbol{x}) \leq \nu$, we have

$$r_{\text{comp}} - d(\boldsymbol{x}) \leq r_{\text{comp}} - \nu.$$

Since the out-boundary loss $\mathcal{L}_{\text{out}}$ is the sum of the individual contributions for each point in $\mathcal{X}_{\text{comp}}$, increasing the number of points for which $d(\boldsymbol{x}) < \nu$ will increase the overall loss $\mathcal{L}_{\text{out}}$ more than increasing the number of points with $d(\boldsymbol{x}) \geq \nu$. Therefore, the points with the threshold radius ν contribute more to the loss than those outside. Thus, the contributions of points with $d(\boldsymbol{x}) < \nu$ is greater than that of points with $d(\boldsymbol{x}) \geq \nu$. □

Proposition 2 (Decrease in Points Inside ν): If the out-boundary loss $\mathcal{L}_{\text{out}}$ decreases with each iteration step, that is, $\mathcal{L}_{\text{out}}^{(t_2)} < \mathcal{L}_{\text{out}}^{(t_1)}$, then the number of points $\boldsymbol{x}$ such that $d(\boldsymbol{x}) < \nu$ decrease between steps t_1 and t_2.

Proof: For given iterative steps t_1 and t_2, assume that the number of points $\boldsymbol{x}$ such that $d(\boldsymbol{x}) < \nu$ increases between iterative steps, meaning that more points fall within the threshold ν at step t_2 than at step t_1. From **Lemma 1**, we know that the contribution to the out-boundary loss $\mathcal{L}_{\text{out}}$ from points within the threshold ν is greater than the contribution from points outside ν. Specifically, for any point $\boldsymbol{x}$ where $d(\boldsymbol{x}) < \nu$, the contribution to the loss satisfies

$$r_{\text{comp}} - d(\boldsymbol{x}) > r_{\text{comp}} - \nu.$$

Thus, if the number of points $\boldsymbol{x}$ such that $d(\boldsymbol{x}) < \nu$ increase at step t_2, the out-boundary loss $\mathcal{L}_{\text{out}}$ at step t_2 should increase relative to its value at step t_1, since the points inside ν contribution more to the loss. This would imply that the loss at step t_2, $\mathcal{L}_{\text{out}}^{(t_2)}$, is greater than or equal to the loss at step t_1, $\mathcal{L}_{\text{out}}^{(t_1)}$.

However, this contradicts the assumption that $\mathcal{L}_{\text{out}}^{(t_2)} < \mathcal{L}_{\text{out}}^{(t_1)}$, i.e., the loss decreases over steps. Therefore, our assumption that the number of points with $d(\boldsymbol{x}) < \nu$ increases between iterations is false.

Thus, for the optimization process of the out-boundary loss over steps, the number of points $\boldsymbol{x}$ such that $d(\boldsymbol{x}) < \nu$ is decreases between steps t_1 and t_2. □

Corollary 1 (Upper Bound of r): *The radius $r^{(t_1)}$ serves as an upper bound on the maximum distance of drug-like points from the center at t_2 where $t_1 < t_2$. As $r^{(t_1)} > r^{(t_2)}$, fewer compounds lie inside this radius at t_2, implying that the boundary of the drug-like space shrinks and becomes more compact.*

Proof: By **Proposition 1**, the drug boundary radius r, defined as the maximum distance of drug-like points from the center, decreases over steps. In other words, $r^{(t_2)} < r^{(t_1)}$ for $t_2 > t_1$, meaning the boundary becomes tighter as the optimization progresses.

And then, by **Proposition 2**, the number of points $\boldsymbol{x}$ such that $d(\boldsymbol{x}) < \nu$ is decreases over steps for any fixed threshold radius ν. This implies that between steps t_1 and t_2. the number of compounds within the radius $r^{(t_2)}$ decreases more than the number of compounds within the radius $r^{(t_1)}$.

Since $r^{(t_1)}$ encompasses all drug-like points at time t_1 and $r^{(t_2)} < r^{(t_1)}$, we conclude that $r^{(t_1)}$ remains an upper bound on the maximum distance of drug-like points from the center at time t_2 even as the boundary shrinks. Therefore, as r decreases with step, the drug boundary become increasingly compact, with fewer compounds lying within the shrinking boundary. □

Based on the above proofs, we now move on to the proof of **Theorem 1**.

Proof of Theorem 1: By **Proposition 1**, we know that the radius r, which represents the boundary of drug-like points, decreases over steps as the Euclidean distance loss is minimized. This shrinking boundary implies that the space enclosing the drug-like compounds becomes more compact as the optimization proceeds from t_1 to t_2.

From **Proposition 2**, we concluded that if the out-compound loss $\mathcal{L}_{\text{out}}$ decreases over steps, the number of points inside an arbitrary radius ν decreases. Thus, the number of non-drug points within the boundary shrinks as t progresses.

By **Lemma 1**, the contribution to the out-compound loss $\mathcal{L}_{\text{out}}$ from non-drug points inside a given radius ν is larger than from points outside. Hence, as the number of in-boundary points decreases, the out-compound loss decreases, consistent with the assumption that $\mathcal{L}_{\text{out}}^{(t_1)} > \mathcal{L}_{\text{out}}^{(t_2)}$.

According to the **Corollary 1**, the drug boundary radius $r^{(t_1)}$ serves as an upper bound on the maximum distance of drug-like points from the center, and this boundary becomes more compact over steps. As $r^{(t_2)} < r^{(t_1)}$, fewer non-drug points will lie inside the boundary at step t_2. □

Combining these results, we see that as the optimization proceeds, both the drug boundary shrinks and the number of non-drug points within this boundary decreases. Given that $\mathcal{L}_{\text{drug}}$ and $\mathcal{L}_{\text{out}}$ both decrease between steps t_1 and t_2, we conclude that the number of non-drug points inside the boundary $|\mathcal{X}_{\text{in-boundary}}|$ decreases as well.

A.3 Convergence criterion of EM-like optimization

For our EM-like optimization algorithm, we applied a convergence criterion based on the in-boundary compound ratio (ICR) metric. We initially considered using a traditional loss-based convergence criterion, which would directly correspond to the model's objective of distance minimization. However, due to the nature of our distance metric, convergence using a loss-based criterion proved challenging; it occasionally led to expansions or contractions of the latent space that risked numerical instability (e.g., overflow/underflow issues). Consequently, we adopted the in-boundary compound ratio as the convergence criterion with following reasons.

Theoretical Alignment Following the proof of theorem 1 in the Appendix A.2, optimizing the distance metric inherently results in a decrease in the in-boundary compound ratio. This proof establishes a theoretical link between loss minimization and our chosen convergence criterion, indicating that both approaches are consistent with the model's objectives.

Empirical Stability We conducted experiments to empirically compare the performance of our model when using the loss-based criterion versus the in-boundary compound ratio (Table 5). The results show no significant difference in final model accuracy, with a p-value of 0.737 which is greater than 0.05 based on a two-sided paired t-test, demonstrating that the two methods converge to

Table 5: Performances of BOUNDR.E with two different convergence metrics. (ICR: In-boundary compound ratio, Avg.: Average)

Convergence metric	F1 (↑)	IDR (↑)	ICR (↓)	AUROC (↑)	Avg. Precision (↑)	Avg. Epochs (↓)
Time-based split						
ICR	0.826 (0.0486)	0.781 (0.0326)	0.012 (0.0086)	0.973 (0.0075)	0.877 (0.0419)	**47.7 (4.20)**
$\mathcal{L}_{boundary}$	0.833 (0.0463)	0.806 (0.0236)	0.014 (0.0098)	0.973 (0.0071)	0.885 (0.0463)	202.7 (99.20)
Paired t-test p-value	0.737	0.055	0.615	0.956	0.723	
Scaffold-based split						
ICR	0.655 (0.0209)	0.796 (0.0258)	0.063 (0.0079)	0.938 (0.0049)	0.590 (0.0369)	**68.5 (4.39)**
$\mathcal{L}_{boundary}$	0.653 (0.0297)	0.793 (0.0348)	0.063 (0.0059)	0.941 (0.0084)	**0.639 (0.0431)**	174.2 (21.76)
Paired t-test p-value	0.892	0.594	0.937	0.158	0.040	

similar solutions. Furthermore, the average number of training epochs needed for convergence was slightly reduced when using the in-boundary compound ratio, indicating faster stabilization.

A.4 COMPUTATIONAL COMPLEXITY ANALYSIS

In this section, we provide the detailed computational complexity analysis, further supporting our model's efficiency and scalability.

E-step (Boundary Update): The E-step in our model relies on computing the Euclidean distance from the center, with a time complexity linear in both the number of samples (N) and the dimensionality (D) of the data, resulting in $O(N \times D)$. This ensures that the boundary update is scalable even for high-dimensional datasets.

M-step (Neural Network Optimization): In the M-step, the primary computational effort involves neural network optimization. If we denote H as the number of layers, F_h as the number of operations in layer h, and N as the dataset size, then the complexity for a forward pass is $O(N \cdot \sum_{h=1}^{H} F_h)$. Given that the backward pass is approximately twice as computationally expensive, the overall complexity for each EM iteration is $O(N \times D) + O(N \cdot \sum_{h=1}^{H} F_h)$.

These complexities illustrate the model's linear behavior with respect to data size and dimensionality, making it efficient for large-scale drug discovery tasks. To validate these claims empirically, we trained our model with approximately 200 drugs and 2,000 non-drug compounds around 100 epochs using single NVIDIA RTX 3090 GPU, and the total training time was consistently under 5 minutes, demonstrating the alignment between theoretical analysis and practical performance.

A.5 MULTIPLE-EM APPROACH FOR AVOIDANCE OF LOCAL OPTIMA

Avoiding local optima and searching for globally optimal parameters is the core challenge of machine learning. However, classical EM algorithms, including K-means clustering and GMMs, are prone to local optima convergence due to their deterministic and hill-climbing nature of monotonic increase in likelihood, which leads to the model's sensitivity to initialization conditions.

Our model is optimized through the Adam optimizer, a stochastic approach for gradient descent that allows flexibility in escaping EM algorithm's monotonic increases during training. On top of this, the biomedical knowledge-aligned embedding space offers an informative initialization point; however, we aimed to develop a more direct solution to address the initialization sensitivity of our framework.

Inspired by successful strategies in EM-based models, such as the Multiple Expectation maximizations for Motif Elicitation (MEME) gene motif search algorithm (Bailey & Elkan, 1995), we initialize our boundary optimization process multiple times from different random seeds (for our experiments, $0 \sim 9$) and retain the best-performing model based on the validation set performance without any reliance on the test data. This approach has proven effective in enhancing performance by mitigating the risk of poor local optima.

Table 6: Key differences between binary classification, PU-learning setting and proposed definition of drug-likeness prediction.

	Binary classification	PU-learning	One-class Drug-likeness prediction
Goal	Decision boundary between positive and negative	Decision boundary between positive and unseen negative	Boundary around positives (here, approved drugs)
Train set composition	Positive + Negative	Positive + Unlabeled	Drug + Compound
Positive data distribution	Positives (P_{positive})	Positives (P_{positive})	X_{drugs} as subset of X_{compound}
Unlabeled data distribution	- (Only negative data)	$P_{\text{positive}} + P_{\text{negative}}$ (unseen)	X_{compound}
Assumption of unlabeled dataset	-	Representative of P_{positive} and P_{negative}	Biased subset of intractable X_{compound}
Characteristics	Strong reliance to negative set, lower generalizability	Reliance to unlabeled set, lower generalizability	Low reliance to compound set, higher generalizability
Objective	Risk minimization with cross-entropy	Risk minimization with class prior and cross-entropy	Metric learning (one-class hypersphere)

A.6 Problem formulation details and comparison with PU learning

Our problem setting roots on the idea to rescue any non-drugs from the compound libraries by not treating any as 'negative drugs'. This motivation naturally led us to apply an one-class classification based approach.

On the other hand, PU learning typically assumes that the distribution of unlabeled data, $P_{\text{unlabeled}}$, can be expressed as a mixture model: $P_{\text{unlabeled}} \sim P_{\text{positive}} + P_{\text{negative}}$. This leads to training objectives rooted in empirical risk minimization that assume a tractable and bounded space of both positive and negative examples with the dataset as a representative subset of such space. In this context, PU methods often aim to minimize classification error with cross entropy-based loss functions by estimating the contribution of a negative distribution, frequently relying on class prior (ratio of positive/negative in the dataset) estimates.

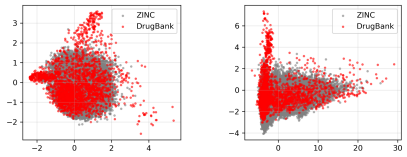
Conventional methods in drug-likeness prediction mainly employ binary classification and sometimes Positive-Unlabeled (PU) learning frameworks, seeking to classify compounds by minimizing the risk of misclassification between positive (drug-like) and negative (non-drug-like) examples with cross entropy-based objectives. However, these approaches rely on defined negative sets or a representative dataset from P_{negative} distribution, which may not be feasible in the vast and partially known chemical space.

In contrast, our formulation of the drug-likeness prediction task does not assume a well-defined P_{negative}. The chemical space is vast, partially explored, and inherently complex, with any sampled "negative" set non-representative of the true distribution of non-drug compounds. Therefore, instead of attempting to estimate a boundary between positive and potential negatives, we propose a one-class classification framework that constructs a drug-likeness boundary to capture the compact space of drug-like compounds directly, optimized based on distance-based metric learning terms. We summarize the key differences between binary classification, PU-learning and our proposed problem definition of drug-likeneess prediction in Table 6.

B Initial Study Details

Scaffold-based distribution of approved drugs We analyzed 2,610 approved drugs from DrugBank using the Bemis-Murcko scaffold split, which partitions molecules into rings and the linker atoms between them. This decomposition resulted in 1,324 unique scaffold sets, with an average of 1.97 molecules per scaffold. These findings indicate a well-dispersed distribution of approved drugs in the chemical space, with minimal structural overlap. Notably, 1,074 scaffold sets (81.1%) contained only a single compound, further emphasizing the low scaffold redundancy among approved drugs.

Evaluating how models generalize to unseen scaffolds is crucial given the extreme sparsity of the scaffold distribution and its potential impact on model generalization, which encouraged us to perform a scaffold-based splitting scheme, further detailed in Appendix C.4.



(a) Fingerprint (b) GraphMVP

Figure 7: PCA visualization of embedding spaces of approved drugs (red) and 100k ZINC compounds (gray).

Table 7: Distribution of drugs and compounds in the two latent spaces. Max: Maximum; ICR: In-boundary compound ratio.

Representation	Max. Drug distance	Max. Compound distance	ICR
GraphMVP	29.33	25.78	1.0
Morgan Fingerprint	12.02	10.01	1.0

Distribution of approved drugs in representation spaces To explore the spatial distribution of approved drugs and non-drug compounds, we represented the structural features of 2,610 approved drugs and 100k ZINC compounds in two distinct spaces: Morgan fingerprints and pretrained GraphMVP embeddings (Liu et al., 2022). Morgan fingerprints, a type of circular fingerprint, capture molecular structure by encoding atom environments within a specified radius. Each substructure, or circular neighborhood of bonds, is hashed into a bitstring, where each bit indicates the presence or absence of specific substructures in the molecule. This approach creates a fixed-length binary vector, efficiently capturing the molecular topology. In contrast, GraphMVP uses a GNN-based encoder, pretrained to align 2D and 3D molecular structures, to generate embeddings that reflect both graph-level and spatial information about molecules.

For each representation space, we calculated the center point of the drug embeddings (centroid) and defined the drug boundary as the maximum distance from the centroid to any drug. We then computed the distance of all 100k ZINC compounds from this centroid to determine the in-boundary compound ratio (ICR).

Our results indicate that all 100k ZINC compounds were positioned within the drug hypersphere in both the Morgan Fingerprint and GraphMVP spaces. Specifically, the maximum distance of approved drugs from the centroid (i.e., the drug radius) was consistently smaller than the maximum distance of ZINC compounds, confirming that non-drug compounds are distributed further from the drug center in both embedding spaces (Table 7).

C Experimental Details

C.1 Overview of Softened CLIP and Geodesic Mixup

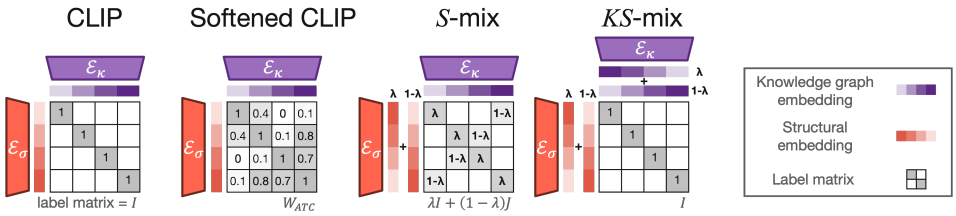


Figure 8: Comparison of contrastive losses using structural encoder $\mathcal{E}_\sigma$ and knowledge encoder $\mathcal{E}_\kappa$. CLIP enforces pair-wise similarity between knowledge graph and structural embeddings from a single entity. Softened CLIP allows pair-wise similarity between knowledge graph and structural embeddings to match the prior similarity matrix (W_{ATC}). S-Mix (and K-Mix), KS-Mix performs intra-modality interpolation.

C.2 Multi-modal Alignment Spaces

Biomedical knowledge graph space To represent the biomedical context of drugs, we use embeddings from DREAMwalk (Bang et al., 2023), which has shown efficacy in tasks of drug-disease

association prediction and drug repurposing. DREAMwalk employs a heterogeneous skip-gram model to encode entities from the Multi-scale Interactome (MSI) network (Ruiz et al., 2021) into a 300-dimensional vector space. The MSI network integrates information on drugs, genes, diseases, and Gene Ontology terms, enriching each drug representation with biomedical knowledge. We utilize the embeddings of 1,449 approved drugs from DREAMwalk for alignment with their structural representations.

Molecular Fingerprint Space For the structural representation of drugs, we use Morgan Fingerprints, a widely adopted method that encodes molecular structures based on substructure patterns. In this study, we employ 1,024-dimensional Morgan Fingerprints for multi-modal alignment, capturing the structural diversity of the molecules.

C.3 Semantic drug similarity calculation with ATC codes

Anatomical Therapeutic Chemical Classification of drugs The ATC classification system categorizes drugs based on their therapeutic, pharmacological, and chemical properties. Each drug is assigned a unique ATC code that reflects its primary mechanism of action and target area. The hierarchy is naturally a tree-structured acyclic graph, and on the highest level (Level 1) exists 14 foundational categories, including A (Alimentary tract and metabolism), B (Blood and blood forming organs), C (Cardiovascular system), and more.

A direct modeling of such complex hierarchical structure as prior knowledge in model training is challenging. In order to retain the essence of the hierarchical ATC relationships without complex adjustments to the architecture that may significantly increase computational overhead and complicate the model training process, we utilized the concept of semantic similarities between terms within the hierarchy and integrated them as prior knowledge to our softened CLIP loss.

Information Content (IC) We adopt the semantic similarity measure introduced by Jiang & Conrath (1997). To quantify the semantic similarity of drugs within the ATC hierarchy, we first need to calculate the Information Content (IC) of each entity. IC measures how informative an entity is, based on its frequency or position within a hierarchical structure. For a term c, IC is inversely proportional to the number of child terms $N_{child}(c)$, meaning that terms with fewer descendants have higher IC, as they provide more specific information. The IC for a term in a tree-structured hierarchy is computed as:

$$IC(c) = 1 - \frac{\log(N_{\text{child}}(c) + 1)}{\log(N_{\text{child}}(\text{root}))}$$

This formulation ensures that IC values are normalized within the range $[0, 1]$, where the root entity has an IC of 0.

Semantic Similarity Given two entities c_1 and c_2 and their Most Informative Common Ancestor (MICA), the semantic distance between them is calculated as:

$$\text{dist}(c_1, c_2) = IC(c_1) + IC(c_2) - 2 \times IC\big(\text{MICA}(c_1, c_2)\big)$$

Since the maximum possible distance is 2 (when IC is 1 for both entities), we normalize the distance into a similarity score in the range $[0, 1)$ using the following equation:

$$\text{sim}(c_1, c_2) = 1 - \left(\frac{\text{dist}(c_1, c_2)}{2}\right)$$

We compute pairwise similarities for all drugs based on their ATC codes, generating a similarity matrix $S \in \mathbb{R}^{n \times n}$, where n is the number of approved drugs.

C.4 Data splitting schemes

Two data splitting schemes are employed to rigorously evaluate model generalizability to unseen compounds: a scaffold-based split, which ensures structurally novel compounds appear in the test set, and a time-based split, where drugs approved after a certain time point are assigned to the test set. Since the structural complexity of approved drugs tends to increase over time, with molecular

properties diverging (Stegemann et al., 2023), the time-based split is considered a more challenging evaluation compared to scaffold-based splits.

To simulate real-world drug discovery conditions, where the chemical space is much larger than the number of approved drugs, we follow a multi-step procedure: first, split the approved drugs into train-valid-test sets in an 8:1:1 ratio, then sample 10 times the number of test drugs from the 100k ZINC compounds to account for the larger compound space.

C.4.1 SCAFFOLD-BASED SPLIT

In drug discovery, scaffold diversity is a key concern, as new drugs often emerge from novel scaffolds that were previously untested. The scaffold-split evaluation aligns closely with these real-world scenarios, making it a more rigorous and realistic test of generalization than a random split, where similar scaffolds are likely to appear in both training and test sets.

Drugs are first grouped based on their scaffolds, defined using Bemis-Murcko scaffolds (Bemis & Murcko, 1996), which capture core molecular ring systems and linkers, ensuring that structurally similar drugs are grouped together. Then, the scaffold sets are split into 10 parts for 10-fold cross-validation (CV), with an 8:1:1 ratio for train, validation, and test sets. Each fold ensures that test sets contain unseen scaffolds. The 100k ZINC compounds are also grouped by Bemis-Murcko scaffolds, then split similarly to match the number of drug scaffolds in each fold. For the test set, ZINC scaffolds are sampled to include 10 times the number of drugs.

Our pilot study demonstrates how prediction performance significantly decreases when using scaffold-split compared to randomly splitted setting (Table 8), indicating that the model's ability to handle unseen scaffolds is inherently more challenging. This underscores the necessity of scaffold-split as a more appropriate evaluation scheme for understanding the impact of scaffold sparsity and further evaluate the models' generalizability.

Table 8: Prediction performances of BounDr.E when applied on different split schemes. Our model displays significant decrease in prediction performances when applied with scaffold split, a splitting scheme to evalutate the models' generalizability in the sparse distribution of approved drugs' scaffolds. The best performance and comparable values (p-value < 0.05) are marked in bold.

	F1	IDR	ICR	AUROC	Average Precision
Scaffold-based split	0.655 (0.0209)	**0.796 (0.0258)**	0.063 (0.0079)	**0.938 (0.0049)**	0.590 (0.0369)
Random split	**0.689 (0.0142)**	0.742 (0.0291)	**0.041 (0.0060)**	**0.942 (0.0037)**	**0.663 (0.0379)**
Paired t-test p-value	4.4E-4	4.6E-4	1.6E-04	0.082	0.008

C.4.2 TIME-BASED SPLIT

The properties of approved drugs have evolved over the past decades, particularly with the emergence of new therapeutic modalities and technologies. For example, kinase-targeted drugs and biologics became prominent in the 2000s, leading to an increase in molecular complexity, larger molecular weights, and drugs that often fall outside traditional Rule-of-5 constraints (DeGoey et al., 2017). Additionally, the advancement of drug delivery systems has allowed for a higher range of LogP values (lower solubility) among approved drugs (Vargason et al., 2021).

Drugs are first split based on their approval date, with approximate splits of 8:1:1 for train, validation, and test sets. The cut-off years are 2000 and 2011. Drugs approved before 2000 are assigned to the training set, those approved between 2000 and 2010 to the validation set, and drugs approved after 2011 to the test set. Then, The ZINC compound scaffolds are sampled following the same procedure as the scaffold-based split, ensuring 10 times more compounds in the test set.

To validate that our time-based split reflects these temporal trends, we have conducted a detailed analysis of drug properties over the periods represented in our dataset (Table 9). Specifically, we tracked changes in key chemical characteristics (e.g., molecular weight, LogP, polar surface area) across different temporal splits, observing clear shifts that align with known trends in drug development.

Table 9: Molecular properties averaged over drugs in the train set (approved before 2011) and test set (approved since 2011). Drugs in the test set show significant difference from the train set drugs, according to the temporal evolution of approved drugs. (Ro5: Number of passed criterions with the Lipinski's Rule of Five)

	Ro5	Molecular Weight	LogP	Polar Surface Area
Train (Before 2011)	3.652739	398.120084	2.142421	100.041105
Test (Since 2011)	3.379032	540.368339	2.937724	137.452177
Paired t-test p-value	0.000396	0.000583	0.024349	0.033635

C.5 Cross-compound dataset evaluation

We have further performed the performed cross-dataset validation using 10,000 molecules sampled from each of PubChem and ChEMBL databases. PubChem contains a vast array of bioassays covering numerous biological targets, while ChEMBL provides curated information on chemical compounds linked to bioactivity against biological targets. These external repositories are widely recognized for their breadth and diversity in assay-centric compound data. We have carefully examined how these datasets complement our original validation set, ZINC20, and their distributions compared with approved drug distribution.

Specifically, we first measured the distributions of three key molecular properties in drug discovery: molecular weight (Mw), LogP and polar surface area (PSA) (Figure 9). The distances between the distributions were computed using 1-Wasserstein distance metric, which display the similarity between ChEMBL compounds and DrugBank approved drugs, followed by PubChem then ZINC20 compounds.

However, the pairwise Tanimoto similarity distribution of molecular fingerprint between DrugBank and other three compound sets reveal that PubChem molecules display the highest average similarity (0.112) compared to ZINC20 (0.111) and ChEMBL (0.013) (Figure 10) Overall, the dissimilarity between datasets demonstrate the uniqueness of each database, and these discrepancies necessitate cross-dataset evaluation for testing the generalizability of drug-likeness prediction models.

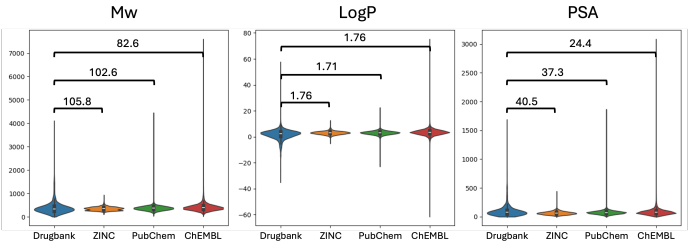


Figure 9: Distribution of molecular properties of DrugBank, ZINC20, PubChem and ChEMBL datasets. The numbers between the distributions represent the Wasserstein distance between the two distributions.

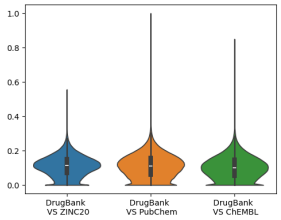


Figure 10: Distribution of pairwise similarities between DrugBank and compound datasets.

C.6 Model Parameterization and Training Details

The chosen hyperparameter search space (Table 10) aligns with prior work in drug-likeness prediction and molecular property prediction, where 2-3 layers with 256-1024 dimensions are commonly used due to their balance between expressiveness and computational efficiency. The selected configuration was validated through a search on a validation set.

Multi-modal alignment Our multi-modal alignment encoders consists of 2-layer multi-layer perceptrons (MLPs) with LayerNorm and ReLU activation. The aligned space is set to `output_dimension=512`. The model is trained using the Adam optimizer (Kingma, 2014) with a `learning_rate=0.001` and `batch_size=32`.

EM-like boundary optimization For models requiring boundary optimization, we use a 2-layer MLP architecture with LayerNorm, ReLU activations, and a `hidden_dimension=512`. When

generating latent spaces, the `output_dimension` is set to 2. The model is trained with the Adam optimizer (Kingma, 2014) using a `learning_rate=0.0005` and `batch_size=1024`.

Table 10: Hyperparameter search space and selected values.

Parameter	Search space	Selected value
Alignment_hidden_dim	[512]	512
Alignment_num_layers	[2,3]	2
Alignment_drop_out	[None, 0.1]	0.1
λ_{soft} (Soft CLIP loss weight)	[0.01, 0.1, 0.5, 1]	0.1
Boundary_hidden_dim	[128,512,1024]	512
Boundary_out_dim	[2,16,128,512]	2
Boundary_num_layers	[2,3,4]	2
Boundary_drop_out	[None, 0.1]	0.1
Boundary_learning_rate	[1e-4, 5e-4, 1e-3]	5e-4
Boundary_batch_size	[256, 512, 1024]	1024
α (drug boundary percentile)	[90, 95, 99, 99.9, 100]	95
λ_{out} (out-boundary loss weight)	[0.1, 1, 1.5, 2]	1

C.7 Baselines

C.7.1 Drug-likeness prediction models

DrugMetric DrugMetric[1] (Li et al., 2024) is an unsupervised drug-likeness prediction model based on JT-VAE (Jin et al., 2018) and Gaussian Mixture Models (GMMs). JT-VAE encodes molecules as tree-structured graphs of predefined substructures, with the VAE generating a latent space that follows a Gaussian distribution. Ensemble of GMMs are applied to model this latent space for predicting drug-likeness, and the drug-likeness score is computed using a Wasserstein distance-based metric.

DeepDL DeepDL[2] (Lee et al., 2022) introduces two models: (1) an unsupervised LSTM-based model for drug-likeness scoring and (2) a PU learning-based Graph Convolutional Network (GCN) for binary drug-likeness classification. The LSTM model predicts the next token likelihood based on a molecule's string representation, aggregating these probabilities into a drug-likeness score. As this method does not perform strict classification, we focus on the PU learning GCN for comparison.

D-GCAN D-GCAN[3] (Sun et al., 2022) is a graph convolution attention network designed for binary drug-likeness classification. The model encodes molecular subgraphs into atom-level vector embeddings using graph convolutional layers, followed by graph attention layers, global sum pooling, and dense layers to learn representations from molecular structures. We reproduce results using the official repository.

C.7.2 General classifiers

To comprehensively evaluate our model's performance in drug-likeness prediction, we compare it against a range of classifiers for binary classification, PU-learning, and one-class classification tasks. Each model is trained on Morgan fingerprint vectors of dimension 1,024 as molecular input representations.

For comparisons with plain MLP-based architectures, we ensured that both our model and the baselines had identical numbers of layers and parameters. Specifically, each baseline was adjusted to match the total parameter count and architectural capacity of our model, ensuring comparable expressibility. For machine learning-based baseline models, we conducted limited search across a range of hyperparameters, including number of estimators. This search was performed using cross-validation to ensure that the most effective configurations were applied consistently across all models.

[1] github.com/renly0313/DrugMetric
[2] github.com/SeonghwanSeo/DeepDL
[3] github.com/JinYSun/D-GCAN

Binary classifiers For binary classification of drugs and non-drugs, we compare our model with traditional machine learning classifiers, including **Support Vector Machine (SVM)** (Boser et al., 1992) and **eXtreme Gradient Boosting (XGBoost)** (Chen & Guestrin, 2016). XGBoost is a gradient-boosting framework that excels in handling structured data and is widely used for molecular property prediction tasks due to its ability to capture complex patterns in sparse input spaces. SVM constructs a hyperplane (or multiple hyperplanes) to separate data points in high-dimensional space, often using a Radial Basis Function (RBF) kernel to model nonlinear decision boundaries. Both models have demonstrated strong performance in molecular property prediction, often surpassing neural network-based models for certain biological endpoints (Wu et al., 2023). For XGBoost model, we searched its `number of estimators` parameter among [50, 100, 200] and chose 100 as the best parameter.

PU-learning baselines Positive-Unlabeled (PU) learning algorithms are well-suited for scenarios where only positive examples (drug-like compounds) and a large set of unlabeled examples are available. We benchmark our model against two PU-learning methods:

- **Naive PU** (Li & Liu, 2003): This method uses the Rocchio classification algorithm, which computes centroids for the positive class and an unlabeled set to form a decision boundary. We adapt this approach with a neural network classifier identical to our model to capture more complex decision boundaries in molecular data.
- **nnPU** (Kiryo et al., 2017): nnPU is an advanced PU-learning algorithm that mitigates overfitting by introducing a non-negative correction term in the risk estimator. This method has shown strong empirical performance in cases where positive and unlabeled data exhibit significant overlap, providing a more robust solution for PU-learning tasks in drug discovery.

One-Class Classification Baselines One-class classification methods are designed to distinguish a single target class (e.g., drug-like compounds) from all other compounds without explicitly modeling the negative class. We evaluate the following one-class models:

- **OCSVM** (Schölkopf et al., 2001): One-Class Support Vector Machines (OCSVM) estimate the support of a high-dimensional distribution, fitting a hyperplane that encompasses most of the positive (drug-like) examples. This is widely used in anomaly detection tasks, including outlier detection in chemical spaces.
- **SVDD** (Tax & Duin, 2004): Support Vector Data Description (SVDD) is an extension of SVMs for one-class classification, which minimizes the radius of a hypersphere that encloses the positive data points. The method is particularly effective in constructing compact decision boundaries around the positive class.
- **DeepSVDD** (Ruff et al., 2018): DeepSVDD extends SVDD by utilizing deep neural networks to learn a transformation of input data into a latent space, where the decision boundary is optimized. This method is well-suited for handling high-dimensional and non-linear representations of molecular structures, making it a strong baseline for drug-likeness prediction tasks in high-dimensional spaces.

D NOTATION

Data Sets

$\mathcal{X}_{\text{comp}}$	the set of all chemical compounds	$\mathcal{X}_{\text{in-boundary}}$	the set of non-drugs inside the boundary
$\mathcal{X}_{\text{drug}}$	the set of drug-like compounds	$\boldsymbol{z}_{\text{drug}}$	the set of embedded drug compounds
$\mathcal{X}_{\text{out}}$	the set of pseudo-negatives	D	the set of batch data

Embedding Spaces and Arrays

$\mathcal{S}$	the structural embedding space	$\boldsymbol{s}_{\text{comp}}$	the structural embedding vector
$\mathcal{K}$	the biomedical knowledge embedding space	$\boldsymbol{k}_{\text{drug}}$	the knowledge embedding vector
$\mathcal{U}$	the unified latent space	$\mathcal{Z}$	the latent space at EM-like training

Functions

$\mathcal{E}_\sigma$	a structural encoder from space $\mathcal{S}$ to $\mathcal{U}$	$C(\cdot)$	the contrastive loss function
$\mathcal{E}_\kappa$	a knowledge encoder from space $\mathcal{K}$ to $\mathcal{U}$	$\mathcal{L}(\cdot)$	the loss function
f_θ	an encoder from space $\mathcal{U}$ to $\mathcal{Z}$	$\odot$	the dot-product similarity operator
$\mathcal{B}$	a hyperspherical boundary	$d(\cdot)$	the Euclidean distance from the boundary center

Parameters

$\boldsymbol{c}$	the center of the drug-like compounds	ρ	the in-boundary compound ratio
r	the radius of the smallest hypersphere	τ	the scaling temperature factor
r_{comp}	the radius for all compounds	η	learning rate
t	the number of iteration steps	ϵ	convergence tolerance
θ	neural network parameters	ν	an arbitrary threshold radius

E Additional Evaluation Results

E.1 Rank-based evaluation

Since the core concept of our drug-likeness prediction problem lies in treating compound dataset as potential drugs, using classification-centric metrics including F1 score, is not perfectly fit for evaluation of drug-likeness prediction. Since our dataset does not have absolute negative samples, we here provide further evaluation of models using average precision, precision@k and recall@k metrics in Table 11. These metrics further measure how well models identify drug-like compounds among the vast chemical space.

Table 11: Drug-like compound ranking performance with time-based split setting. Mean and standard deviation of 10 fold cross-validation are provided. Best performances marked in bold and second-best underlined.

	Avg. Precision	Prec@50	Prec@100	Prec@200	Rec@50	Rec@100	Rec@200
FP-SVM	0.724 (0.0174)	0.852 (0.0160)	0.777 (0.0090)	0.540 (0.0067)	0.344 (0.0065)	0.627 (0.0072)	0.871 (0.0108)
FP-XGB	0.775 (0.0213)	0.868 (0.0458)	0.773 (0.0155)	0.538 (0.0117)	0.350 (0.0185)	0.623 (0.0125)	0.868 (0.0188)
FP-OCSVM	0.148 (0.0022)	0.280 (0.0000)	0.180 (0.0100)	0.132 (0.0023)	0.113 (0.0000)	0.145 (0.0081)	0.212 (0.0037)
FP-SVDD	0.143 (0.0022)	0.240 (0.0000)	0.144 (0.0049)	0.108 (0.0040)	0.097 (0.0000)	0.116 (0.0040)	0.174 (0.0064)
FP-DeepSVDD	0.097 (0.0157)	0.098 (0.0569)	0.106 (0.0420)	0.101 (0.0274)	0.040 (0.0230)	0.085 (0.0339)	0.164 (0.0442)
FP-nnPU	0.706 (0.0261)	0.846 (0.0457)	0.713 (0.0279)	0.500 (0.0101)	0.341 (0.0184)	0.575 (0.0225)	0.807 (0.0163)
FP-PU	0.720 (0.0214)	0.864 (0.0367)	0.712 (0.0248)	0.502 (0.0147)	0.348 (0.0148)	0.574 (0.0200)	0.810 (0.0237)
DeepDL	0.886 (0.0374)	0.976 (0.0233)	0.846 (0.0393)	0.513 (0.0172)	**0.448 (0.0215)**	**0.777 (0.0390)**	**0.942 (0.0289)**
DGCAN	0.613 (0.1874)	0.512 (0.2461)	0.464 (0.2520)	0.499 (0.1687)	0.217 (0.1047)	0.393 (0.2126)	0.884 (0.2857)
BoundR.E	**0.908 (0.0096)**	**0.988 (0.0098)**	**0.923 (0.0135)**	**0.569 (0.0070)**	0.398 (0.0040)	0.744 (0.0108)	0.918 (0.0113)

E.2 Drug-Compound Identification with Scaffold Split

Drug-compound identification performances with scaffold split are provided in Table 12.

E.3 Cross-dataset evaluation results

We extended our experiments to cross-dataset evaluation two additional well-established datasets: PubChem and ChEMBL. Both datasets encompass a wide range of chemical scaffolds and molecular properties, making them suitable for testing our model's ability to generalize across varied chemical

Table 12: Drug-like compound identification performance with scaffold-split setting. Mean and standard deviation of 10 fold cross-validation are provided. Best performances marked in bold and second-best underlined.

	MCC (↑)	F1 (↑)	IDR (↑)	ICR (↓)	IDR/ICR (↑)
FP-SVM	0.597 (0.0120)	0.597 (0.0090)	**0.951 (0.0286)**	0.122 (0.0061)	7.798 (0.2746)
FP-XGB	0.599 (0.0166)	0.602 (0.0181)	0.941 (0.0281)	0.118 (0.0112)	8.059 (0.6524)
FP-OCSVM	0.060 (0.1159)	0.179 (0.0582)	0.551 (0.2165)	0.446 (0.0172)	1.223 (0.4332)
FP-SVDD	-0.132 (0.0287)	0.151 (0.0033)	0.881 (0.0203)	0.970 (0.0022)	0.909 (0.0211)
FP-DeepSVDD	-0.120 (0.1607)	0.147 (0.0294)	0.834 (0.1787)	0.938 (0.0423)	0.890 (0.1871)
FP-nnPU	0.546 (0.0213)	0.550 (0.0182)	0.923 (0.0385)	0.146 (0.0110)	6.362 (0.4021)
FP-PU	0.549 (0.0239)	0.555 (0.0188)	0.907 (0.0491)	0.135 (0.0130)	6.776 (0.5185)
DrugMetric	-0.028 (0.0794)	0.160 (0.0238)	0.692 (0.2932)	0.690 (0.3452)	1.115 (0.3095)
D-GCAN	0.599 (0.0340)	0.594 (0.0456)	0.859 (0.0966)	0.109 (0.2808)	8.145 (1.9174)
DeepDL	0.528 (0.0298)	0.523 (0.0403)	0.889 (0.0608)	0.137 (0.0248)	6.661 (0.8857)
BOUNDR.E	**0.626 (0.0211)**	**0.655 (0.0209)**	0.796 (0.0258)	**0.063 (0.0079)**	**12.808 (1.4438)**

spaces. As shown in Tables 13 and 14, our model maintains stable prediction performance across these diverse datasets, demonstrating its ability to generalize effectively beyond the training data.

Table 13: Drug-like compound identification performance on scaffold-split setting with cross-dataset evaluation setting. Mean and standard deviation of 10 fold cross-validation are provided. Best performances marked in bold.

	PubChem + DrugBank					ChEMBL + DrugBank				
	F1	IDR	ICR	Avg. Precision	AUROC	F1	IDR	ICR	Avg. Precision	AUROC
FP-SVM	0.268 (0.0194)	0.835 (0.0734)	0.434 (0.0174)	0.334 (0.1912)	0.795 (0.0759)	0.371 (0.0519)	0.681 (0.1427)	0.195 (0.0200)	**0.494 (0.1982)**	0.819 (0.0768)
FP-XGB	0.254 (0.0209)	0.810 (0.0804)	0.451 (0.0197)	0.320 (0.1181)	0.773 (0.0741)	0.358 (0.0589)	0.675 (0.1411)	0.206 (0.0213)	0.469 (0.1839)	0.814 (0.0784)
FP-OCSVM	0.179 (0.0582)	0.551 (0.2165)	0.446 (0.0172)	0.366 (0.2717)	0.576 (0.1949)	0.179 (0.0582)	0.551 (0.2165)	0.446 (0.0172)	0.366 (0.2717)	0.576 (0.1949)
FP-SVDD	0.151 (0.0033)	**0.881 (0.0203)**	0.970 (0.0022)	0.055 (0.0019)	0.235 (0.0173)	0.151 (0.0033)	**0.881 (0.0203)**	0.970 (0.0022)	0.055 (0.0019)	0.235 (0.0173)
FP-DeepSVDD	0.147 (0.0294)	0.834 (0.1787)	0.938 (0.0423)	0.080 (0.0146)	0.415 (0.1224)	0.147 (0.0294)	0.834 (0.1787)	0.938 (0.0423)	0.080 (0.0146)	0.415 (0.1224)
FP-nnPU	0.244 (0.0182)	0.833 (0.0727)	0.504 (0.0637)	0.240 (0.0816)	0.749 (0.0556)	0.327 (0.0525)	0.666 (0.1337)	0.241 (0.0374)	0.380 (0.1999)	0.778 (0.0812)
FP-PU	0.241 (0.0265)	0.664 (0.1219)	0.379 (0.0528)	0.228 (0.0556)	0.702 (0.0560)	0.311 (0.0495)	0.653 (0.1477)	0.250 (0.0311)	0.396 (0.1701)	0.778 (0.0874)
DeepDL	0.170 (0.0199)	0.764 (0.0754)	0.598 (0.0481)	0.092 (0.0112	0.590 (0.0233)	0.195 (0.0389)	0.681 (0.1329)	0.530 (0.1553)	0.102 (0.0196)	0.612 (0.0686)
DGCAN	0.213 (0.0232)	0.775 (0.0643)	0.520 (0.0653)	0.1352 (0.0153)	0.685 (0.0436)	0.314 (0.0620)	0.652 (0.1283)	0.285 (0.2380)	0.211 (0.0601)	0.737 (0.1076)
Ours	**0.501 (0.0232)**	0.759 (0.0441)	**0.126 (0.0148)**	**0.460 (0.0380)**	**0.875 (0.0157)**	**0.513 (0.0451)**	0.746 (0.0281)	**0.117 (0.0190)**	0.435 (0.0889)	**0.869 (0.0258)**

Table 14: Drug-like compound identification performance on time-split setting with cross-dataset evaluation setting. Mean and standard deviation of 10 fold cross-validation are provided. Best performances marked in bold.

	PubChem + DrugBank					ChEMBL + DrugBank				
	F1	IDR	ICR	Avg. Precision	AUROC	F1	IDR	ICR	Avg. Precision	AUROC
FP-SVM	0.223 (0.0046)	0.576 (0.0115)	0.365 (0.0137)	0.177 (0.0085)	0.663 (0.0073)	0.252 (0.0068)	0.385 (0.0079)	0.171 (0.0088)	0.200 (0.0080)	0.624 (0.0077)
FP-XGB	0.216 (0.0087)	0.575 (0.0165)	0.382 (0.0241)	0.214 (0.0256)	0.655 (0.0098)	0.248 (0.0108)	0.415 (0.0103)	0.198 (0.0139)	0.232 (0.0152)	0.638 (0.0123)
FP-OCSVM	0.136 (0.0028)	0.250 (0.0000)	0.248 (0.0052)	0.168 (0.0031)	0.371 (0.0029)	0.136 (0.0028)	0.250 (0.0000)	0.248 (0.0052)	0.168 (0.0031)	0.371 (0.0029)
FP-SVDD	0.139 (0.0024)	0.766 (0.0000)	0.947 (0.0034)	0.143 (0.0020)	0.360 (0.0032)	0.139 (0.0024)	0.766 (0.0000)	0.947 (0.0034)	0.143 (0.0020)	0.360 (0.0032)
FP-DeepSVDD	0.158 (0.0071)	**0.810 (0.0439)**	0.860 (0.0344)	0.096 (0.0132)	0.480 (0.0362)	0.158 (0.0071)	**0.810 (0.0439)**	0.860 (0.0344)	0.096 (0.0132)	0.480 (0.0362)
FP-nnPU	0.212 (0.0116)	0.621 (0.0130)	0.430 (0.0235)	0.139 (0.0135)	0.632 (0.0144)	0.229 (0.0153)	0.447 (0.0333)	0.253 (0.0246)	0.163 (0.0130)	0.616 (0.0215)
FP-PU	0.188 (0.0218)	0.491 (0.1036)	0.381 (0.0941)	0.151 (0.0348)	0.579 (0.0386)	0.217 (0.0285)	0.398 (0.0312)	0.234 (0.0318)	0.176 (0.0310)	0.608 (0.0300)
DeepDL	0.200 (0.0166)	0.786 (0.0618)	0.575 (0.0548)	0.108 (0.0090)	0.621 (0.0285)	0.207 (0.0362)	0.658 (0.0539)	0.506 (0.0707)	0.111 (0.0183)	0.617 (0.0406)
DGCAN	0.256 (0.0377)	0.810 (0.0707)	0.467 (0.1835)	0.155 (0.0267)	0.700 (0.0724)	0.318 (0.0691)	0.639 (0.1352)	0.251 (0.1072)	0.220 (0.0647)	0.739 (0.0732)
Ours	**0.769 (0.0426)**	0.796 (0.0137)	**0.029 (0.0125)**	**0.760 (0.0492)**	**0.941 (0.0093)**	**0.816 (0.0149)**	0.749 (0.0288)	**0.009 (0.0038)**	**0.870 (0.0149)**	**0.950 (0.0047)**

E.4 Zero-shot Toxic Compound Identification

E.4.1 Full table of model performances

We provide the full table of zero-shot toxic compound identification performances on all baseline models in Table 15. The zero-shot prediction was performed using each model trained on DrugBank-ZINC dataset, without any further fine-tuning on the toxic compound sets. False-positive rate was measured to evaluate how correctly each model determines the toxic compounds as 'non-drug-like'. DrugMetric in particular fails to yield predictions for withdrawn compound set since JTVAE is capable of encoding only the scaffolds present in the training set, in this case the combined set of ZINC and DrugBank approved drugs.

Table 15: False-positive rate of toxic compound groups. The best performances and the comparable values (paired t-test p-value < 0.05) are marked in bold.

	Withdrawn	Hepatotoxic	Cardiotoxic	Carcinogenic
FP-SVM	0.98 (0.001)	0.98 (0.001)	0.86 (0.006)	0.98 (0.002)
FP-XGB	0.96 (0.003)	0.96 (0.003)	0.85 (0.010)	0.93 (0.010)
FP-SVDD	0.95 (0.002)	0.93 (0.002)	0.92 (0.003)	0.99 (0.001)
FP-OCSVM	0.69 (0.002)	**0.53 (0.003)**	0.25 (0.006)	0.86 (0.001)
FP-DeepSVDD	0.81 (0.022)	0.80 (0.020)	0.87 (0.032)	0.56 (0.063)
FP-PU	0.95 (0.007)	0.94 (0.005)	0.87 (0.021)	0.85 (0.009)
FP-nnPU	0.95 (0.009)	0.94 (0.007)	0.87 (0.028)	0.86 (0.017)
DrugMetric*	*N/A*	0.77 (0.073)	0.76 (0.118)	0.82 (0.087)
DGCAN	0.91 (0.020)	0.85 (0.023)	0.88 (0.045)	0.95 (0.017)
DeepDL	0.91 (0.016)	0.92 (0.018)	0.85 (0.042)	0.84 (0.025)
BounDr.E	**0.51 (0.014)**	0.54 (0.009)	**0.20 (0.009)**	**0.19 (0.014)**

*DrugMetric fails to infer scaffolds not present in approved drug and ZINC datasets

E.4.2 Error analysis on "partially-withdrawn" drugs

We conducted an in-depth error analysis on the false-positive withdrawn drugs predicted as "in-drug-boundary" by our model (51% in Table 15), identifying a trend of predictions involving drugs referred to as "partially-withdrawn"—drugs that are approved in some regions but withdrawn in others, in contrary to "fully-withdrawn" drugs. This category represents complex cases where the criteria for withdrawal may vary.

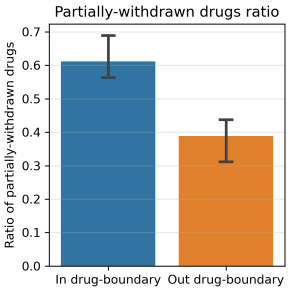


Figure 11: Partially-withdrawn drug ratio between in- and out-drug-boundary sets.

Our analysis across 10 cross-validation trials revealed a significantly higher presence of partially-withdrawn drugs in the in-drug-boundary predicted (false positive) set (61.2%) compared to out-drug-boundary (true negative) ones (38.8%) with p-value of 7.8E-3 (paired t-test)(Fig. 11). This suggests that our model's predictions reflect real-world complexities in regulatory approval, while maintaining a false positive ratio of 0.52, with 60% of these false positives falling into this partially-withdrawn category.

E.5 Additional ablation study results

Effect of Multi-modal Alignment with Softened CLIP Loss We compared our softened CLIP loss with alternative alignment strategies, including CLIP (Radford et al., 2021), Geodesic Mixup (Oh et al., 2024), naive manifold alignment (Ham et al., 2005), and unaligned space (i.e., molecular fingerprints) (Table 2). Our proposed method significantly improves boundary quality due to the enriched representation that aligns molecular structure with biomedical knowledge. The resulting embedding space produces a tighter drug boundary, leading to improved drug-like compound identification performances.

Effect of EM-like Optimization We evaluated the advantage of our EM-like boundary optimization against traditional binary classifiers, PU learners, and one-class models (Table 3). Our model achieves the lowest ICR (or FPR), showcasing the strength of iterative boundary refinement, which iteratively increases the out-boundary compounds (Appendix E.5.1). Figure 12 shows the robustness of our method under increasing compound-to-drug ratios (from 1:1 to 1:100), maintaining performance in more realistic conditions of 1:50 and 1:100 ratios where non-drug compounds vastly outnumber drugs.

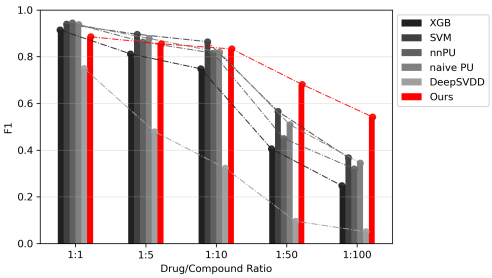


Figure 12: Change of F1 score with the decrease in drug-compound ratio of the test set.

These ablations confirm the complementary nature of multi-modal alignment and boundary optimization in improving drug-likeness prediction.

E.5.1 Effect of EM-like optimization

The core advantage of our method lies in its iterative updates to both the decision boundary and the encoder. Unlike other classifiers including MLP, which relies on fixed embeddings, our algorithm dynamically adjusts the feature space and boundary across multiple iterations as following:

1. An initial, coarse boundary is set using the contrastive embeddings.
2. The encoder refines these embeddings based on feedback from the initial boundary, adjusting the representation.
3. A new boundary is established using these refined embeddings.
4. This process repeats, allowing the model to fine-tune both the decision criteria and the feature space.

This iterative refinement can also be seen in Figure 13, where the ratio of out-boundary compounds increases and converges over time with each EM iteration. This progressive refinement demonstrates the limitations of a static MLP approach, reinforcing the necessity of our iterative EM-like strategy for accurate boundary learning.

E.5.2 Effect of multi-modal alignment with softened CLIP loss

Our multi-modal alignment loss encompases four modules; softened-CLIP loss, S and K-mix, and KS-mix. While softened-CLIP loss is designed to integrate prior knowledge as ATC semantic similarity, geodesic mixup-inspired loss terms—S-mix, K-mix, and KS-mix—facilitate the learning of the intermediate space between conflicting representations. Specifically:

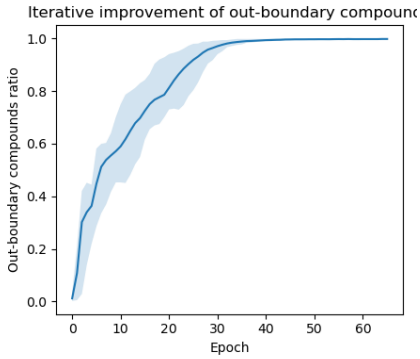


Figure 13: Iterative improvement of out-boundary compound ratio. Line plot shows the average over 10 trials, and area between maximum and minimum values are colored.

- **S-mix & K-mix:** These loss terms focus on intra-space interpolation within the structural (S-mix) and knowledge-based (K-mix) embeddings, respectively. By encouraging the model to interpolate between known data points, it learns a smoother and more continuous embedding space, reducing sensitivity to local conflicts.
- **KS-mix:** This component specifically targets inter-space interpolation, blending structural and biomedical representations. It creates synthetic data points that reflect a balanced compromise between structural and biomedical features, enabling the model to harmonize inconsistencies and achieve a unified representation.

Table 16: Drug-like compound identification with EM-like boundary optimization on embedding space aligned with alignment method ablations on time-based split scheme. Best performance and comparable values in bold.

Alignment method	F1 (↑)	IDR (↑)	ICR (↓)	AUROC (↑)	Avg. Precision (↑)
Ours w/ Original CLIP	0.727 (0.0365)	0.670 (0.0605)	0.018 (0.0066)	0.801 (0.0506)	0.755 (0.0481)
Ours w/o S,K-mix	0.466 (0.1705)	0.745 (0.1058)	0.270 (0.3446)	0.818 (0.1825)	0.420 (0.1995)
Ours w/o KS-mix	0.604 (0.2238)	0.858 (0.0734)	0.241 (0.3782)	0.849 (0.2091)	0.576 (0.2546)
No alignment (only FP)	0.539 (0.0324)	0.571 (0.0176)	0.057 (0.0161)	0.907 (0.0144)	0.557 (0.0461)
Ours (softened CLIP + S,K,KS-mix)	0.826 (0.0486)	0.781 (0.0326)	0.012 (0.0086)	0.973 (0.0075)	0.877 (0.0419)
Ours + Multiple-EM	**0.846 (0.0165)**	**0.799 (0.0184)**	**0.009 (0.0031)**	**0.978 (0.0029)**	**0.908 (0.0096)**

We evaluated the performance of the model by selectively removing each component the final setup (Table 16). The results indicate that each component contributes uniquely to the model's performance. Replacing the softened CLIP loss with the original CLIP loss brought 10 percent point loss in F1 score, highlighting the importance of knowledge integration in our model's accurate performances. Removing both S-mix and K-mix resulted in a drop of 36 percent points in F1 score, indicating their contribution to aligning embeddings across diverse drug classes and scaffolds in each of structural and knowledge spaces. Additionally, without KS-mix, the model showed a reduction of 22 percent point in F1 score, underscoring the importance of a balanced contribution from both structural and semantic features.

Overall, our results show that the combination of all three strategies yields the best performance, with a synergistic effect that improves both classification accuracy and stability, effectively integrating knowledge and simultaneously resolving conflicts between structural and biomedical spaces.

E.6 Filtering AI-generated anti-cancer molecules

E.6.1 Details on utilized property-based filtering criteria

PAINS filter The PAINS (Pan-Assay Interference Compounds) filter is designed to identify and eliminate molecules that are likely to produce false-positive results in high-throughput screening assays. These compounds often interfere with biological assays through non-specific mechanisms such as covalent binding, redox activity, or fluorescence interference. The PAINS filter operates by detecting specific substructures known to cause assay interference. In our pipeline, each compound is scanned against a comprehensive library of PAINS substructure patterns. Compounds that do not contain any of these substructures are considered clean and retained for further analysis. This filter ensures that the remaining molecules have a reduced likelihood of assay-related artifacts, enhancing the reliability of downstream predictions.

Lipinksi's Rule of 5 Lipinski's Rule of Five (Ro5) is a widely accepted guideline to assess the drug-likeness of a molecule based on its physicochemical properties. The rule includes four criteria:

1. Molecular Weight must be less than or equal to 500 Daltons.
2. LogP (Partition Coefficient) must be less than or equal to 5, ensuring favorable lipophilicity.
3. No more than 5 hydrogen bond donors (sum of OH and NH groups).
4. No more than 10 hydrogen bond acceptors (sum of O and N atoms).

Compounds that adhere to all four criteria are considered to have favorable pharmacokinetic properties, such as good oral bioavailability and permeation, and are retained for further consideration. By applying this rule, we effectively filter out molecules that are less likely to succeed in later stages of drug development due to poor absorption or bioavailability.

Predicted IC50 Binding affinity prediction is a critical step for assessing the potential biological activity of a compound. We employed XGBoost models to predict IC50 values, which represent the concentration of a compound required to inhibit a biological process by 50%. These models were trained on bioassay datasets from with IC50 values in ChEMBL database, specifically: BCR-ABL

(CHEMBL2096618), EFGR (CHEMBL203), and CDK6 (CHEMBL2508) (accessed 16 November 2024).

The input features for these models were Morgan molecular fingerprints, which capture key structural and functional aspects of each compound. Compounds predicted to have an IC50 below 10 μM are classified as "active" and retained. This threshold was selected to balance the need for potent biological activity with the feasibility of further development, ensuring that only promising candidates proceed to subsequent stages of evaluation.

E.6.2 Characteristics of in-drug-boundary compounds

In this section, we provide detailed experimental results in investigating the potentials of our model as a complementary data-driven filter in a AI-driven rational drug discovery pipeline. To be specific, our model can serve as an efficient, early-stage filtering tool that can significantly narrow down the search space in large chemical libraries, thereby easing the computational burden on subsequent analyses.

Filtering capability of BounDr.E-integrated pipeline We applied our model to filter 10,000 AI-generated compounds from TargetDiff, using three widely-known anti-cancer targets: BCR, EGFR and CDK6, each targeted by cancer drugs imatinib, erlotinib and ribociclib, respectively. The results demonstrate the outstanding filtering ratio of our approach compared to others (Table 17). Additionally, by initially applying BounDr.E followed by all other filters yielded approximately 0.3% of screened compounds, a very practical number for wet lab validations.

Table 17: Number of filtered compounds by different filters.

Filtering Method	BCR-ABL	EGFR	CDK6
Total Generated	10,543 (100%)	12,550 (100%)	11,496 (100%)
PAINS filter	10,078 (95.7%)	11,878 (94.6%)	10,996 (95.6%)
Rule of Five	4,997 (47.5%)	6,520 (52.0%)	5,782 (50.3%)
Predicted IC50	2,786 (26.5%)	1,018 (8.10%)	4,734 (41.2%)
BounDr.E	300 (2.8%)	374 (3.00%)	264 (2.3%)
All filters−BounDr.E	1,320 (12.5%)	491 (3.9%)	2,710 (23.6%)
All filters	**38 (0.36%)**	**17 (0.15%)**	**47 (0.40%)**

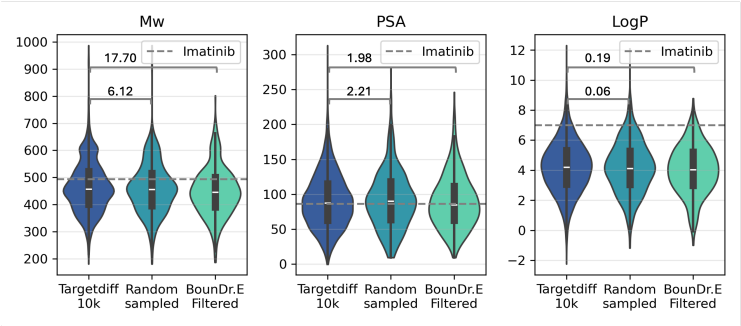


Figure 14: Distribution of molecular properties of Targetdiff generated molecules on BCR protein pocket (PDB: 1OPJ) and its filtered sets. BounDr.E-filtered set shows more distant distribution of molecular properties from the original 10k molecules.

Characteristics of In-drug-boundary compounds After screening with our drug boundary, we retained 300, 374 and 264 in-boundary compounds for each target. For comparison, we randomly sampled the equal amount of molecules (repeated 100 times) and measured key molecular properties of the filtered drugs, including polar surface area (PSA), molecular weight (Mw), and logP.

Figure 14 highlights a significant shift in key drug-like properties in the BounDr.E-filtered compounds compared to randomly sampled compounds generated for BCR. Furthermore, Table 18

Table 18: Various traditional drug-likeness measures of Targetdiff generated molecules and filtered sets. Most desirable values are in bold. (SAS: Synthetic Accessibility Score; Avg.: Average)

Target protein	**BCR** (PDB: 1OPJ)			**EGFR** (PDB: 4HJO)			**CDK6** (PDB: 5L2T)		
Groups	**SAS (↓)**	**Avg. QED (↑)**	**Ro5 ratio (↑)**	**SAS (↓)**	**Avg. QED (↑)**	**Ro5 ratio (↑)**	**SAS (↓)**	**Avg. QED (↑)**	**Ro5 ratio (↑)**
TargetDiff 10k	4.956	0.425	0.474	5.562	0.410	0.521	5.378	0.384	0.507
Random sampled*	4.958	0.426	0.475	5.586	0.409	0.514	**5.353**	0.382	0.508
BounDr.E filtered	**4.930**	**0.433**	**0.532**	**5.477**	**0.413**	**0.546**	5.523	**0.392**	**0.532**

* Repeated 100 times

shows a marked increase in average QED, Ro5-passing ratio and Synthetic Accessibility Score (SAS), implying the sampled compounds are more drug-like whens cross-measured through conventional metrics. In detail, the Wasserstein distance of the three properties from the starting 10k compounds reveal that our filtering strategy significantly alters the distribution of the key molecular properties of filtered compounds (Table 19).

Table 19: Properties of filtered Targetdiff-generated molecules and their distributional distance from to the original distribution of 10k generated molecules for three protein targets (BCR, EGFR, CDK6). (W-distance: 1-Wasserstein distance)

Groups	**W-distance from BCR-10k**			**W-distance from EGFR-10k**			**W-distance from CDK6-10k**		
	Mw	**PSA**	**logP**	**Mw**	**PSA**	**logP**	**Mw**	**PSA**	**logP**
Random sampled	6.122	**2.205**	0.058	6.882	**2.566**	0.099	5.997	**5.584**	**0.266**
BounDr.E filtered	**17.695**	1.979	**0.187**	**16.834**	2.298	**0.168**	**10.903**	5.032	0.135

* Repeated 100 times

Table 20: PDF of approved drugs with the distribution of three key molecular properties on different filtered sets, originated from 10k generated molecules for three protein targets (BCR, EGFR, CDK6). (Mw: Molecular weight; PSA: Polar surface area)

Groups	**PDF of imatinib (BCR)**			**PDF of Erlotinib (EGFR)**			**PDF of Ribociclib (CDK6)**		
	Mw	**PSA**	**logP**	**Mw**	**PSA**	**logP**	**Mw**	**PSA**	**logP**
TargetDiff 10k	4.00E-03	1.02E-03	2.26E-01	2.88E-03	5.10E-03	2.14E-01	3.64E-03	9.49E-03	2.06E-01
Random sampled*	**4.02E-03**	1.03E-03	2.27E-01	2.84E-03	5.05E-03	2.14E-01	**3.68E-03**	**9.57E-03**	2.06E-01
BounDr.E filtered	3.94E-03	**1.05E-03**	**2.32E-01**	**3.09E-03**	**5.32E-03**	**2.26E-01**	3.49E-03	8.87E-01	**2.18E-01**

* Repeated 100 times

In addition, the Probability Density Function (PDF) of approved drugs, imatinib, erlotinib and ribociclib among the three properties also increased, implying identifying the approved drugs among the filtered molecules is more likely with our filtered set (Table 20).

The Wasserstein distance and Probability Density Function (PDF) of imatinib properties are measured using gaussian KDE. The properties of the approved drugs are computed with rdkit python package.

These findings demonstrate the practical utility of our model in filtering AI-generated compounds, enabling efficient virtual screening and improving the quality of early-stage candidates.

E.7 Statistical validation results

In this section, we provide the statistical validation results for the tables in the main text (Tables 1 $\sim$ 5), computed with one-sided paired t-test to compare the significance compared to the best performing models (Tables 21 to 23).

Table 21: Statistical validation for drug-like compound identification performance with time-split setting (Table 1). Mean and standard deviation of 10 fold CV are provided. Best performance and its comparable results (paired t-test $p < 0.05$) are marked in bold

	F1 (↑)	IDR (↑)	ICR (↓)	AUROC (↑)	Avg. Precision (↑)
SVM	1.0	1.0	1.0	1.0	1.0
XGB	1.0	1.0	1.0	1.0	1.0
OCSVM	1.0	1.0	1.0	1.0	1.0
DeepSVDD	1.0	0.9999	1.0	1.0	1.0
nnPU	1.0	1.0	1.0	1.0	1.0
naive PU	1.0	1.0	1.0	1.0	1.0
DrugMetric*	1.0	1.0	1.0	1.0	1.0
DGCAN	0.9947	**Best**	0.9311	0.9988	0.8841
DeepDL	0.9999	0.9905	0.9999	**Best**	0.4459
BounDr.E	**Best**	1.0	**Best**	0.07378	**Best**

Table 22: Statistical validation for drug-like compound identification with EM-like boundary optimization on embedding space aligned with different alignment methods (Table 2). One-sided paired t-test p-values of 10 trials compared to the best model are provided. Lowest and its comparable results (paired t-test $p < 0.05$) are marked in bold.

Alignment method	F1 (↑)	ICR (↓)
No Alignment (only FP)	1.0	0.7489
Manifold Alignment	1.0	**Best**
CLIP	1.0	0.4685
Geodesic Mixup	0.9998	0.001325
Ours - softCLIP	0.9992	**8.50E-06**
Ours	**Best**	**9.86E-08**

Table 23: Statistical validation for drug-like compound identification with different classifiers on knowledge-aligned space (Table 3). Best performance in bold and second best underlined. One-sided paired t-test p-values of 10 trials compared to the best model are provided. Lowest and its comparable results (paired t-test $p < 0.05$) are marked in bold.

Aligned space	F1 (↑)	ICR (↓)
+ MLP	1.0	1.0
+ SVM	**Best**	0.9863
+ XGB	1.0	1.0
+ naive PU	1.0	0.9999
+ DeepSVDD	1.0	1.0
+ Ours − EM	1.0	0.9978
+ Ours	0.9816	**Best**

Table 24: Statistical validation for false-positive rate of toxic compound groups (Table 4). One-sided paired t-test p-values of 10 trials compared to the best model are provided. Lowest and its comparable results (paired t-test $p < 0.05$) are marked in bold.

	Withdrawn	Hepatotoxic	Cardiotoxic	Carcinogenic
XGB	1.0	1.0	1.0	1.0
OCSVM	1.0	**Best**	1.0	1.0
nnPU	1.0	1.0	1.0	1.0
DrugMetric	N/A	0.9616	0.9995	1.0
DGCAN	1.0	1.0	1.0	1.0
DeepDL	1.0	1.0	1.0	1.0
BOUNDR.E	**Best**	0.9875	**Best**	**Best**

*DrugMetric fails to infer scaffolds not present in approved drug and ZINC datasets