Evaluation of deep learning tools for chromatin contact prediction

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Abstract

Three-dimensional chromatin organization is essential for gene regulation and is commonly measured using Hi-C contact maps. Recent deep learning models have been developed to predict Hi-C maps from genomic and epigenomic features. However, their relative performance and biological interpretability remain poorly understood due to the lack of systematic evaluation. Here, we present a comprehensive benchmarking framework that evaluates five Hi-C prediction models: C.Origami, Epiphany, ChromaFold, HiCDiffusion, and GRACHIP, across predictive accuracy, visual fidelity, and downstream biological analyses. Among them, Epiphany consistently achieved the best overall performance, combining high accuracy, cross-cell-type generalization, realistic map quality, and reliable loop recovery. The framework further shows that epigenomic features, particularly CTCF binding and chromatin co-accessibility, are the primary drivers of accurate Hi-C pattern prediction. Notably, although many models incorporate multiple omics inputs, only a limited subset substantially contributes to performance. This manuscript clarifies model behaviour and provides guidance for developing and interpreting Hi-C prediction methods.

Keywords

3D genome organization, enhancer–promoter interactions, Hi-C prediction, deep learning

1. Introduction

Gene expression is tightly controlled by a complex network of regulatory mechanisms that ensure genes are expressed at the right time, location, and level [1]. Among the various layers of regulation, transcriptional regulation plays a central role [2]. At this level, transcription factors (TFs) bind to promoter regions and to distal regulatory elements such as enhancers to modulate gene activity. Because enhancers can act over long genomic distances and regulatory interactions are often combinatorial, the architecture of gene regulatory networks (GRNs) is highly complex, dynamic, and context-dependent. A key source of complexity arises from the fact that many genes are controlled by distal enhancers, which may be located tens to hundreds of kilobases, or even megabases, away from their target promoters. Early studies often assumed that an enhancer regulates its nearest gene along the linear genome sequence [3]. However, this distance-based assumption has proven to be overly simplistic because the genome is folded in three-dimensional (3D) space within the nucleus, allowing distal regulatory elements to physically contact promoters [4]. Accordingly, enhancers defined from chromatin accessibility data (ATAC-seq cCREs) frequently act over long genomic distances: 80.94% are located more than 2 kb away from the nearest transcription start site [5]. Moreover, these distal enhancers tend to be less conserved and more cell type-specific. For instance, ZRS enhancer is located in the intron of LMBR1, around 1 Mb away from SHH, which controls limb expression [6]. Enhancer variants within the FTO locus were shown to act through long-range chromatin interactions to regulate IRX3/IRX5 rather than the nearest gene [7].

To capture these distal interactions, researchers have used technologies to decipher 3D chromatin contacts, among which Hi-C has become the most widely used [8]. Hi-C is a genome-wide chromosome conformation capture (3C) technique in which chromatin is crosslinked, restriction-digested, and proximity-ligated, followed by paired-end sequencing to identify genomic loci that are physically close in the nucleus. Hi-C revealed that genome organization is hierarchical. At the megabase scale, chromosomes segregate into A and B compartments corresponding to active and inactive chromatin,

respectively. At an intermediate scale, the genome is partitioned into topologically associating domains (TADs), regions with enriched internal interactions. At a finer scale, chromatin loops connect specific loci, often linking enhancers and promoters. Chromatin looping within TADs constrains enhancer–promoter communication and contributes to cell-type-specific gene regulation. [8]. One of the major advantages of Hi-C is its scalability and high throughput, allowing the detection of fine-scale chromatin interactions such as enhancer-promoter loops [9],10]. Furthermore, Hi-C data can be integrated with other omics datasets to provide a comprehensive view of gene regulation. However, mapping 3D genome interactions with Hi-C remains technically challenging and prohibitively costly. High-resolution contact maps (e.g., ~5 kb resolution requiring ~2 billion read pairs) are therefore available for only a limited number of cell types and experimental conditions.. To overcome the scarcity of 3D genome data, researchers have increasingly turned to computational prediction methods, particularly deep learning approaches. These models aim to infer chromatin interactions or Hi-C contact maps using multi-omics data. In computational terms, this task is often described as modality prediction, where one or more data modalities are used to predict another modality. This strategy reduces experimental costs and enables reconstruction of missing biological layers.. In parallel, sequence-to-function models have emerged as a related direction. These approaches learn regulatory information directly from genomic DNA sequence and predict diverse molecular readouts such as chromatin accessibility, transcription factor binding, and gene expression, thereby linking genotype to gene regulatory function [11]. Together, modality prediction and sequence-based modeling aim to computationally recover regulatory information that is otherwise experimentally difficult to obtain. . Several successful examples of modality prediction have been reported. For instance, BABEL predicts chromatin accessibility from gene expression, while MultiVI can impute missing RNA or ATAC profiles in partially observed single-cell multiome datasets [12], [13].

Recent years have seen a rapid expansion of deep learning-based models predicting 3D genome organization from DNA sequence and commonly generatedepigenomic tracks. Convolutional neural network (CNN)-based models have been particularly successful at predicting genome-wide chromatin

interactions [14], while transformer-based models have further advanced the field by capturing long-range dependencies through self-attention mechanisms [15]. Hybrid architectures that combine CNNs and transformers have shown additional improvements by leveraging the strengths of both, extracting local sequence features with CNNs and modelling long-range relationships with transformers [16]. The development of these models has significantly improved our ability to predict Hi-C maps from accessible data sources such as Assay for Transposase-Accessible Chromatin using sequencing (ATAC-seq) and Chromatin Immunoprecipitation of CCCTC-binding factor (CTCF ChIP / CUT & RUN). Various other architectures, including some generative models, have been applied to this problem too [17]. These approaches not only aim to maximize predictive accuracy but also to enhance the quality, generalizability, and biological interpretability of predicted Hi-C maps. However, chromatin architecture is strongly cell-type specific. Models relying only on DNA sequence lack regulatory context and therefore tend to predict similar structures across cell types. This limitation has motivated the development of multimodal and context-aware models that incorporate additional molecular measurements. The models compared in this study differ substantially in their input modalities and architectural assumptions. Epiphany predicts Hi-C contact maps using only epigenomic tracks, such as chromatin accessibility and histone modifications, enabling cell-type-specific prediction [18]. ChromaFold instead focuses on using single-cell ATAC-seq accessibility profiles, allowing recovery of cell-type-specific chromatin interactions from a few number of modalities, particularly single cell ATAC [19]. GRACHIP integrates DNA sequence and genomic features within a graph neural network framework to explicitly model relationships between interacting loci [20]. HiCDiffusion predicts chromatin interactions directly from only genomic DNA sequence using a transformer encoder combined with a diffusion-based generative module. This model primarily investigates whether DNA sequence alone can sufficiently capture cell-type-specific Hi-C contact maps [17]. In contrast, C.Origami, which is often used as a benchmark model, primarily learns general chromatin folding patterns from sequence-derived features and does not inherently model cell-type-specific regulatory variation. [21] These approaches aim not only to improve prediction accuracy but also to reconstruct

biologically meaningful chromatin features, enabling inference of genome organization from widely available multi-omics data such as ATAC-seq and CTCF profiling.

However, a major challenge remains: with many deep learning models now available, which one performs best, and under what criteria? Previous studies proposing new approaches have typically evaluated them against only a limited set of baseline models (e.g., C.Origami [21] or Akita [22]), focusing primarily on accuracy while neglecting other aspects such as generalization and biological relevance. Consequently, there is no standardized framework for evaluating or comparing deep learning models for Hi-C prediction, making it difficult to assess their relative strengths and weaknesses. A comprehensive benchmarking effort must therefore consider multiple evaluation dimensions, including robustness across cell types, and the biological plausibility of predicted structures.

In this manuscript, we aim to systematically compare five representative models: C.Origami [21], Epiphany [18], ChromaFold [19], HiCDiffusion [17], and GRACHIP [20]. The evaluation focussed on multiple perspectives, including predictive accuracy, visual quality of the generated maps, generalization ability across different cell types or species, and biological relevance for downstream analyses. In addition, we performed ablation analyses to assess the necessity and contribution of each input modality to model performance. These criteria were used to determine how closely the predicted Hi-C maps resemble experimental data and how effectively each model captured meaningful chromatin interactions. Through this benchmarking analysis, we identified the architectural designs, input features, and training strategies that contribute to superior model performance. Ultimately, this framework established a reference for standardized evaluation in future studies of 3D genome modelling and promoted the reliable use of in silico Hi-C prediction in downstream applications.

2. Results

We compared five representative models for 3D chromatin contact prediction - C.Origami, Epiphany, ChromaFold, HiCDiffusion, and GRACHIP, using the evaluation workflow summarized in Figure 1. For

each model, input data were preprocessed according to the recommended settings, and predicted Hi-C contact maps were generated across four human cell lines and 22 chromosomes. The predicted maps were then compared with experimental Hi-C data to assess model performance from multiple complementary perspectives. The predictions generated by each model were assessed using three criteria: (1) predictive accuracy, (2) image quality, and (3) loop detection performance. Predictive performance was firstly evaluated by direct comparison of predicted and experimental contact matrices using three quantitative metrics: mean squared error (MSE), insulation score correlation, and observed-over-expected (O/E) Hi-C correlation. To further examine the contribution of input information, ablation analyses were performed by removing individual modalities and measuring the resulting performance changes. Second, we evaluated the visual realism of predicted contact maps using the Fréchet Inception Distance (FID). Finally, predicted contact maps were processed with a loop-calling pipeline, and the detected chromatin loops were compared with loops identified from experimental Hi-C data to assess downstream biological utility.

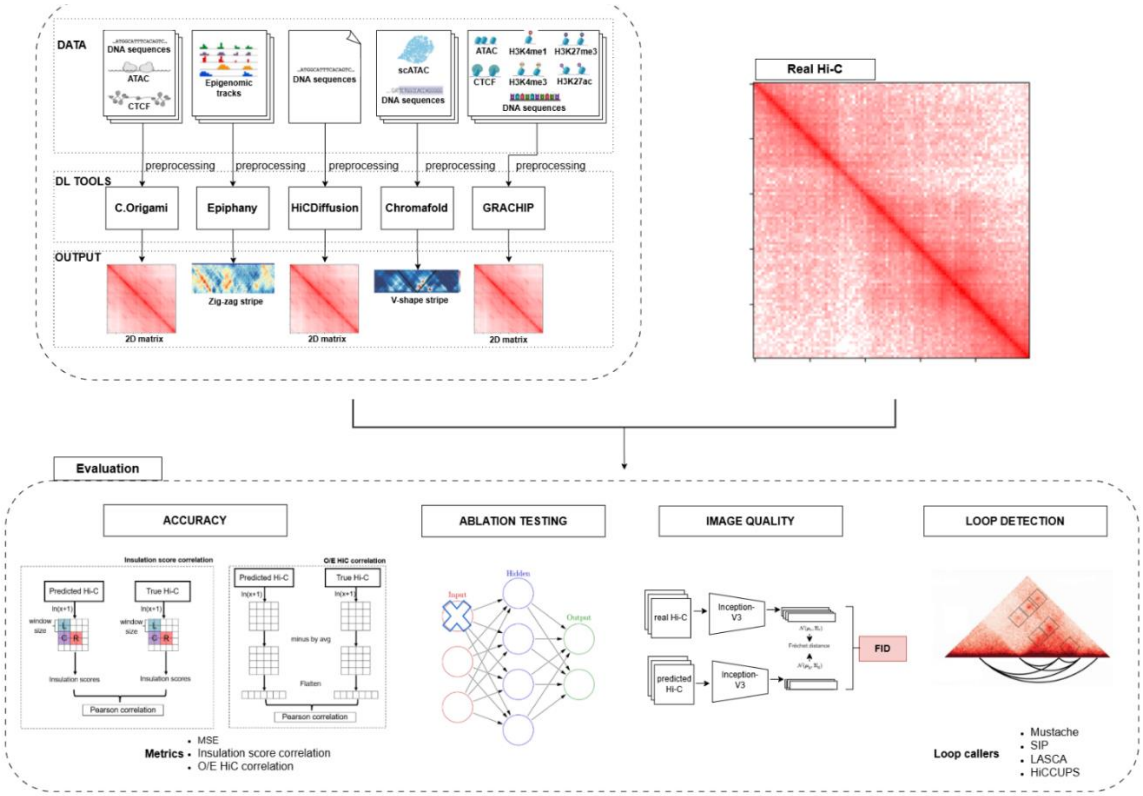


Figure 1: Procedure for comparing predicted Hi-C data with ground truth Hi-C data

Accuracy performance evaluation

In this section, we compared the predictive accuracy of each model across different cell lines and performed a cross-model benchmark to identify the best-performing approach. Model performance was assessed using the quantitative performance metric Mean Squared Error (MSE) and the more biologically relevant metrics (insulation score correlation, and observed/expected (O/E) Hi-C correlation) (Methods). The insulation score correlation measures how well a model captures local chromatin domain structure by comparing insulation profiles, whereas O/E Hi-C correlation measures similarity of 3D contact patterns after correcting for distance-dependent contact decay.

Within-model generalization across cell types and chromosomes

First, each model was evaluated independently by examining its performance by MSE scoring across different cell lines and chromosomes (Figure 2). The top panel showed a bubble plot summarizing model performance across chromosomes and cell lines, while the bottom panel displayed violin plots illustrating the distribution of scores. Three notable patterns were observed. First, an unexpected pattern was observed for HiCDiffusion, ChromaFold, and GRACHIP, where performance on the training cell line was lower than on unseen cell lines.. Second, the variability of MSE scores was very large, with training performance ranging from near 0 to near 1 depending on the chromosome and cell line. Third, C.Origami showed very high performance on the training data but extremely low values on unseen cell lines, with scores close to 0, suggesting an completely failure of prediction (C.Origami). Although previous reports that C.Origami was known to have limited ability to capture cell-type-specific regulatory variation, performance values near zero are unexpected, as they would imply a complete loss of predictive signal.Therefore, the near-zero scores cannot be explained solely by overfitting, as even an overfitted model would be expected to retain some predictive signal. Instead, this observation suggests that the MSE-based metric may not accurately reflect the true predictive performance of the model under this evaluation setting.

Comparing the models based on the insulation score correlation, the results were more consistent and easier to interpret (Figure 3). First, the variance across chromosomes and cell lines appeared more stable and followed a tighter distribution, rather than spanning the extremely wide range observed with MSE. Second, the relationship between training and unseen data aligned with expectations, with performance on the training cell line being slightly higher than performance on unseen cell lines. Third, although C.Origami showed reduced generalization to unseen cell lines, its insulation score correlation remained within a reasonable range (approximately 0.5), suggesting decreased performance rather than the apparent complete failure implied by the normalized MSE results. A similar trend was also observed for the O/E Hi-C correlation (Supplementary Figure S1)

This discrepancy indicated that MSE was not well-suited for comparing these models. This discrepancy indicates that MSE is not appropriate as a universal comparison metric because the models are trained with different optimization objectives. Epiphany directly minimizes a pixel-wise mean squared error (MSE) between predicted and experimental Hi-C maps (optionally combined with an adversarial loss). In contrast, C.Origami is trained to reproduce structural features of chromatin organization, with performance evaluated using measures such as insulation score and distance-stratified correlation rather than strict intensity matching. ChromaFold is optimized to predict normalized interaction signals and significant contacts from accessibility patterns, while GRACHIP learns interaction relationships through a graph-based representation of chromatin interactions. HiCDiffusion further departs from reconstruction-based training by employing a generative diffusion framework that prioritizes realistic map structure instead of minimizing pixel-wise error. Because these models minimize different objectives during training, an external MSE metric often rewards models trained for numerical reconstruction and penalizes those trained to recover structural or biological features. Therefore, MSE cannot fairly represent real predictive performance across models. Moreover, MSE quantified only pixel-level differences between contact matrices and therefore did not directly measure whether biologically meaningful structures (such as TAD boundaries) were preserved. Finally, because MSE is unbounded (ranging from 0 to infinity), min–max normalization and score inversion could distort

interpretation; a low inverted normalized score reflected poorer relative performance within the benchmark rather than true model failure. For these reasons, subsequent evaluations focused primarily on insulation score correlation and observed-over-expected (O/E) Hi-C correlation, which have been widely used to assess the structural similarity and biological validity of predicted Hi-C contact maps in previous studies. In particular, prior work evaluating models such as C.Origami, Epiphany, and related methods relied on insulation profiles, normalized Hi-C similarity, and downstream interaction detection rather than pixel-wise reconstruction error.

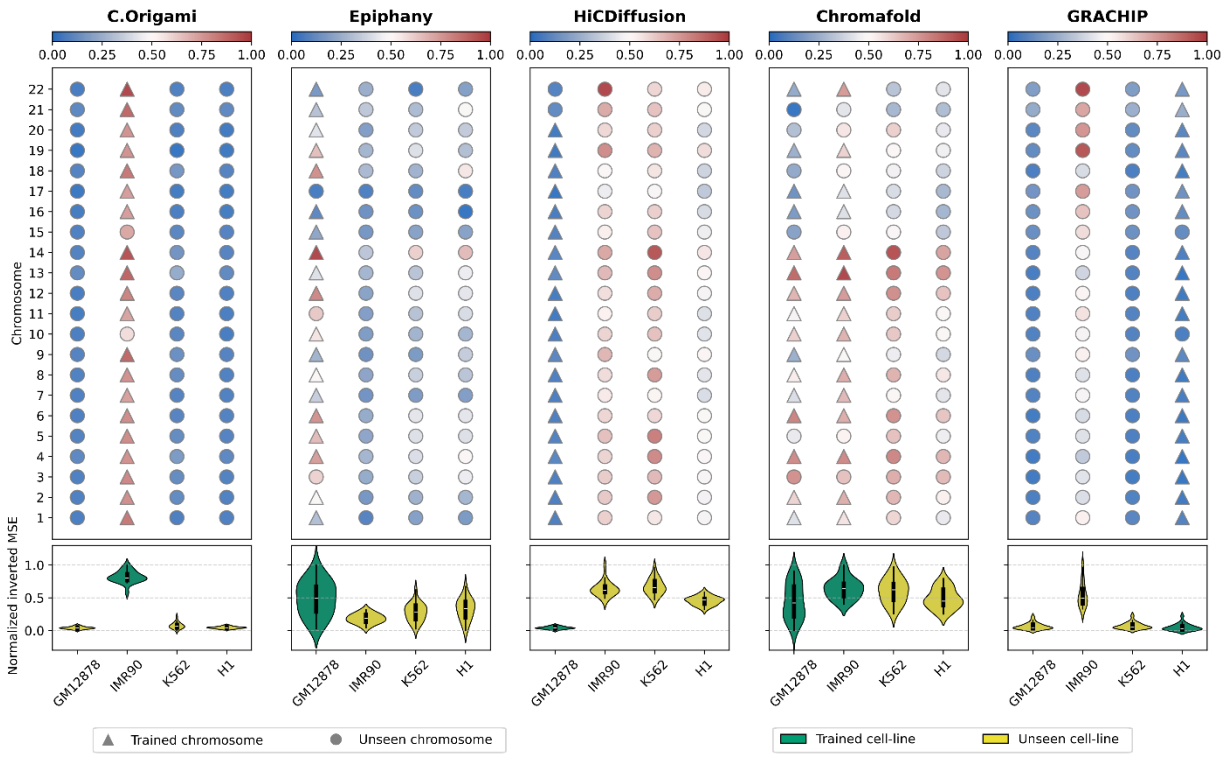


Figure 2. The performance of 5 Hi-C prediction models using normalized inverted MSE. *Top: Bubble plot. The y-axis shows the 22 chromosomes, and the x-axis represents the cell lines. Colors are scaled independently for each cell line. Triangles indicate trained chromosomes, and circles indicate unseen chromosomes. Warmer (red) colors represent higher performance, while cooler (blue) colors indicate lower performance. Bottom: Violin plot showing the distribution of model performance within each cell line. The y-axis denotes the performance scores, and the x-axis corresponds to the cell lines. Green*

indicates trained cell lines, and yellow indicates unseen cell lines. The metric is the the inverted normalized MSE scores, scaled between 0 and 1 (higher values indicating better performance).

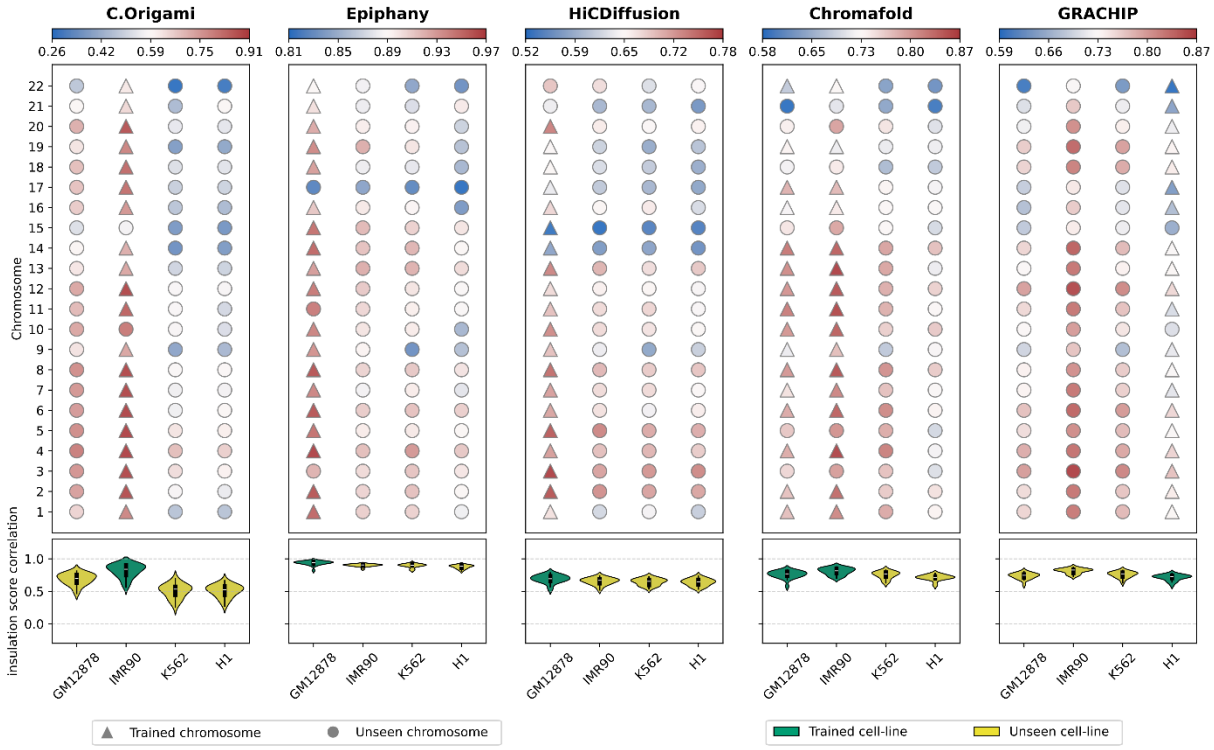


Figure 3. The performance of 5 Hi-C prediction models using insulation score correlation. *Top: Bubble plot. The y-axis shows the 22 chromosomes, and the x-axis represents the cell lines. Colors are scaled independently for each cell line. Triangles indicate trained chromosomes, and circles indicate unseen chromosomes. Warmer (red) colors represent higher performance, while cooler (blue) colors indicate lower performance. Bottom: Violin plot showing the distribution of model performance within each cell line. The y-axis denotes the performance scores, and the x-axis corresponds to the cell lines. Green indicates trained cell lines, and yellow indicates unseen cell lines.*

Another key observation was that model generalization varied substantially (Figure 3). C.Origami performed best on its training cell line (IMR90), achieving insulation and O/E correlations above 0.9, but its accuracy dropped sharply for unseen lines such as K562 and H1. In contrast, Epiphany maintained high performance across all cell lines, with both correlation metrics exceeding 0.9, demonstrating strong transferability of learned chromatin features. Despite relying solely on DNA

223 sequence, HiCDiffusion also generalized well, producing stable correlations above 0.8 across datasets.
224 ChromaFold showed consistent and robust generalization, maintaining correlations above 0.85 even
225 for unseen cell lines. Although trained on GM12878 and IMR90, its performance on IMR90 and H1
226 slightly exceeded that on GM12878, suggesting that the model captured transferable regulatory
227 features rather than overfitting. GRACHIP achieved lower overall performance but showed minimal
228 variation across cell lines, indicating stable, though less accurate, generalization.

229 **Cross-model comparative analysis of Hi-C prediction performance**

230 Subsequently, the models were compared against one another across 22 chromosomes in a specific
231 cell line to identify the strongest performer (Figure 4). The figure reorganizes the previously obtained
232 results and displays the models side by side to enable direct performance comparison. As can be seen,
233 Epiphany achieved the highest overall performance in all metrics, averaging around 0.90 and 0.85,
234 respectively, across all cell lines. ChromaFold followed closely, with strong consistency and minimal
235 variation. C.Origami, again, displayed clear overfitting on the trained cell line, while HiCDiffusion
236 achieved notable accuracy from sequence data alone, although its insulation score correlations were
237 slightly lower than its observed/expected (O/E) Hi-C correlations. GRACHIP ranked lowest, particularly
238 in O/E correlation, around 0.5, reflecting weaker fine-scale reconstruction, though it retained
239 moderate TAD-level (insulations core) accuracy.

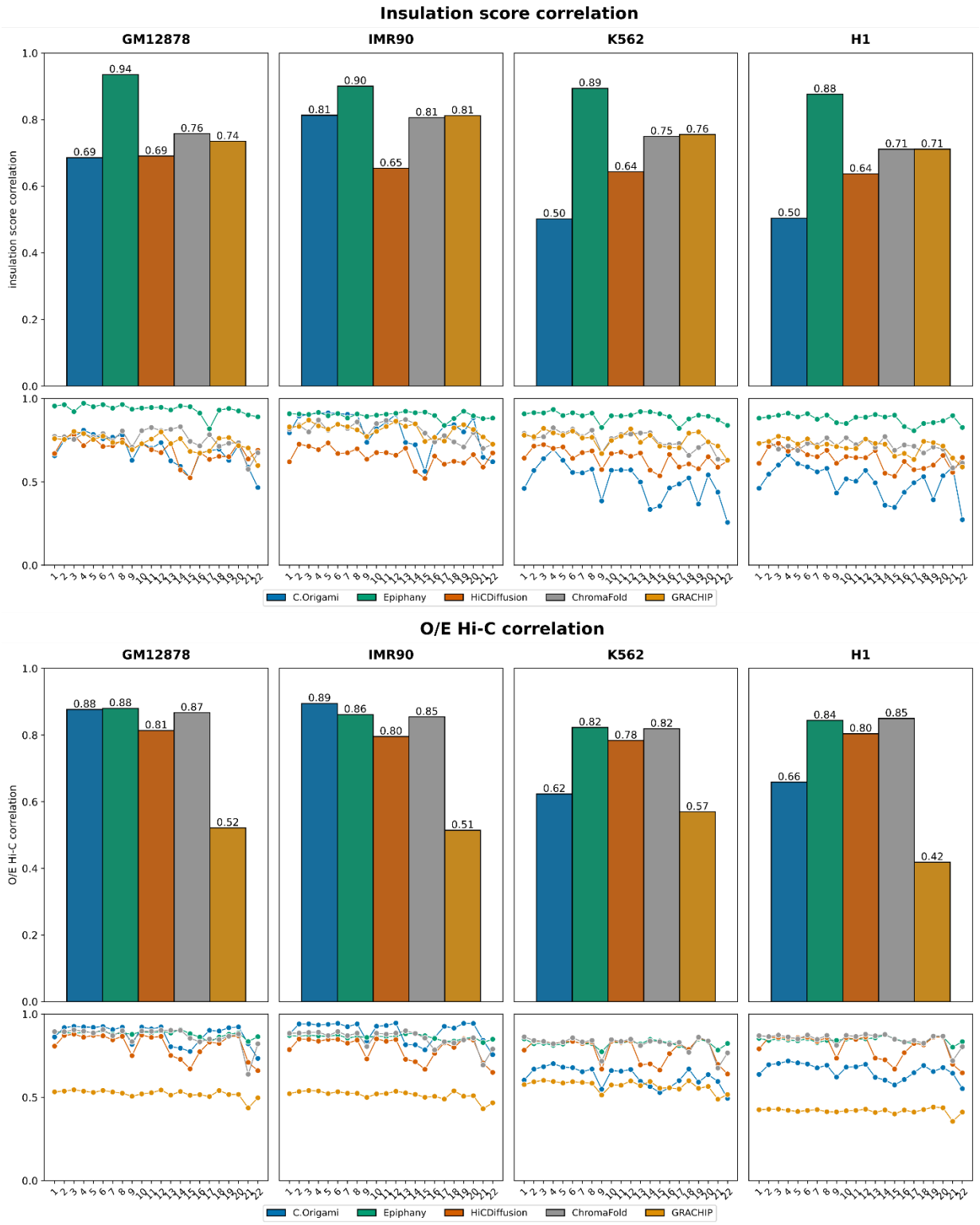


Figure 4. Comparison of model performance for each dataset using insulation score correlation and O/E Hi-C correlation. *Top: Bar plot - The y-axis shows the performance score, and the x-axis lists the models, each represented by a distinct colour. Bottom: Line plots - The y-axis shows the performance*

score across chromosomes, while the x-axis lists chromosome indices. Each line corresponds to a different model, illustrating how model performance varies across genomic regions.

When evaluating performance across individual chromosomes, it was observed that most models exhibited similar trends, consistently struggling with chromosomes 9, 15, 22. This pattern appeared regardless of the specific chromosomes used during training or held out for testing, suggesting that these particular chromosomes might possess structural complexity that were more challenging for models to learn and generalize from. However, despite this challenge, stronger models such as Epiphany and ChromaFold were still able to achieve relatively high scores on these difficult chromosomes.

Ablation analysis

Ablation testing was performed to quantify the contribution of different input data modalities to Hi-C prediction accuracy, thereby identifying which biological signals were most informative for each model. Specifically, the test were conducted to determine how individual input modalities influence Hi-C prediction accuracy and to investigate whether different regulatory signals provide overlapping information. We systematically removed single modalities or biologically related modality groups and measured the resulting change in prediction performance, thereby assessing potential redundancy and compensatory effects among the input tracks.. Due to models with many inputs, only individual modalities and biologically relevant modality groups were tested on four chromosomes (5, 6, 10, and 15). HiCDiffusion was excluded because it relies solely on DNA sequence.

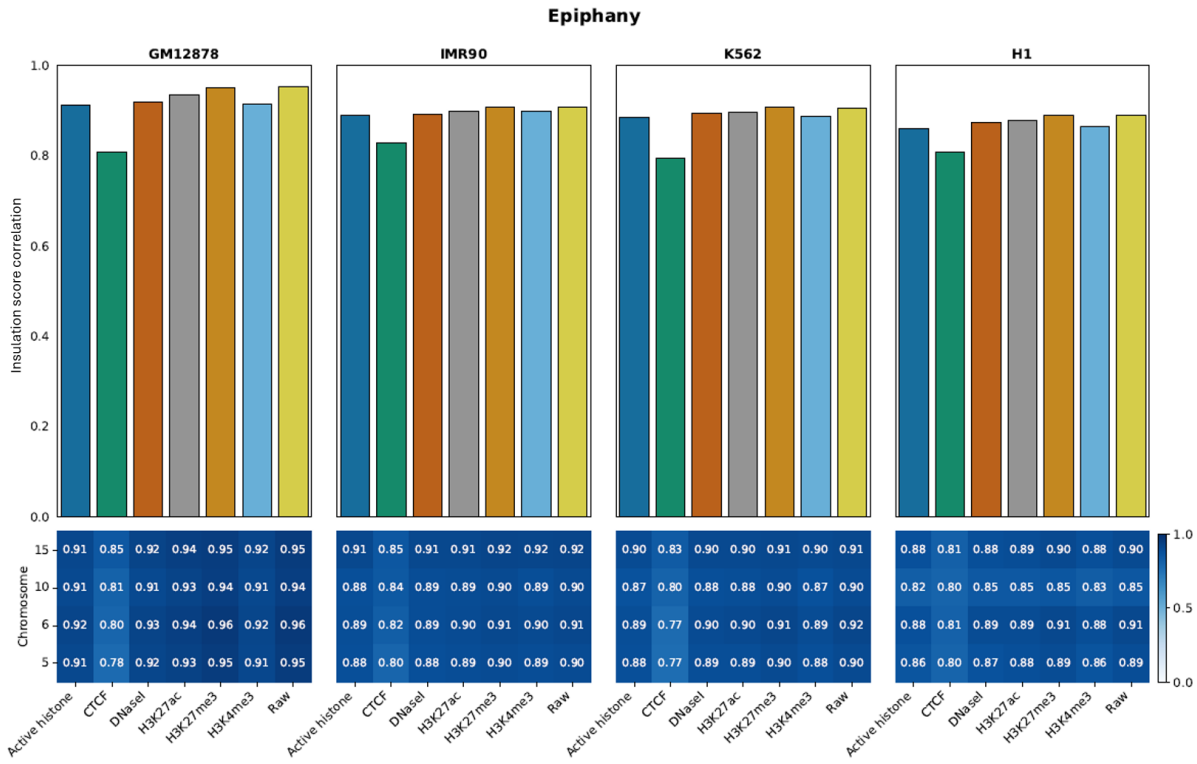


Figure 5. Epiphany ablation performance across modalities, cell lines, and chromosomes, using insulation score correlation. *Top: Bar plot showing ablation results; the x-axis lists the removed modality, and the y-axis shows insulation score correlation. Bottom: Heatmap with chromosomes on the y-axis and removed modalities on the x-axis; each cell's color and value indicate the corresponding performance.*

Figure 5 shows the insulation score–based ablation results for Epiphany across input modalities, cell lines, and chromosomes. Corresponding ablation results for the other models and additional evaluation metrics were provided in the Supplementary Material (Suplemetary Figure 3 – 13). For clarity, Table 1 summarized the most important input modalities for each model, as determined by ablation results using both insulation score correlation and observed/expected (O/E) Hi-C correlation. Following ablation testing, C.Origami showed a pronounced dependence on CTCF input: removing the CTCF track led to a drastic reduction in performance, indicating that it was the most critical modality for accurate prediction. Notably, the combined use of CTCF and ATAC signals further improved predictions, indicating that chromatin accessibility provides complementary information to CTCF

binding. In contrast, DNA and ATAC signals alone contributed little in unseen cell lines, indicating potential overfitting to the training data. Similarly, Epiphany's performance dropped sharply when CTCF was removed (insulation correlation <0.8), whereas excluding DNA or histone marks had minimal effect (Figure 5). For ChromaFold, ablation revealed that co-accessibility information was indispensable: removing this feature led to near-zero performance, indicating that the model depends on relationships between accessible regions rather than accessibility peaks alone. This observation is consistent with the original study, which reported that co-accessibility derived from scATAC-seq provides a substantial improvement over pseudobulk accessibility alone. In addition, removal of the CTCF signal also reduced performance, suggesting that CTCF binding provides complementary structural information that supports accurate prediction. . GRACHIP relied heavily on DNA, with its removal reducing performance to near zero; ATAC-seq also contributed modestly to insulation accuracy. Across models, ablation effects were consistent across chromosomes, suggesting global rather than region-specific dependencies. From all the tests, it revealed that CTCF emerged as the most influential feature in most of models, highlighting its essential role in defining chromatin architecture (Table 1).

Table 1: Summary of important modalities in each model.

Model	Important modalities
C.Origami	1. CTCF ChIP-seq
	2. ATAC
Epiphany	1. CTCF ChIP-seq
ChromaFold	1. scATAC-seq
	2. CTCF motif scores
GRACHIP	1. DNA
	2. ATAC

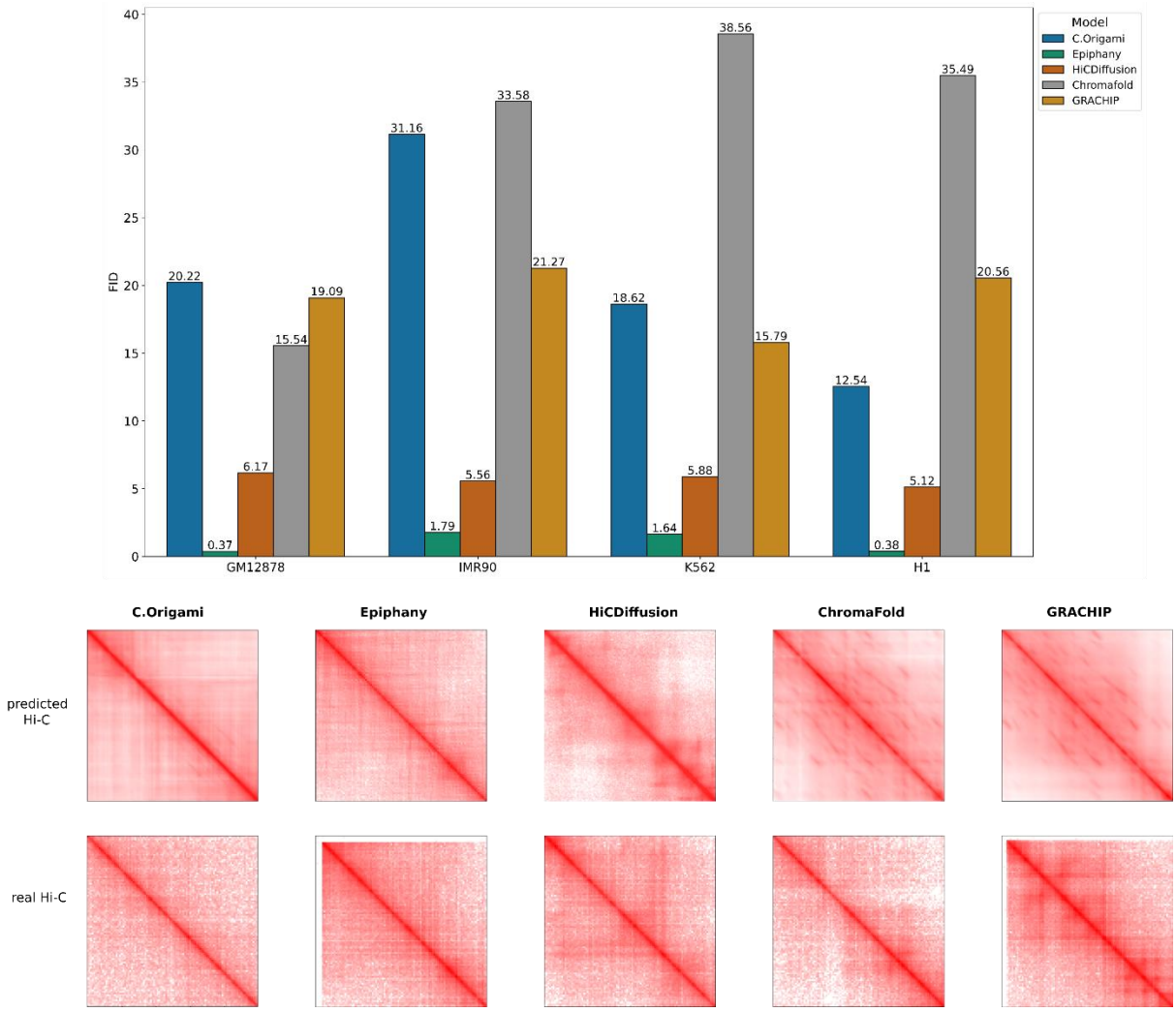


Figure 6. Visual realism of predicted Hi-C contact maps across cell lines. *Top: Bar plot showing FID for each model across cell lines. Bottom: Representative predicted contact maps from each model compared with the corresponding experimental ground-truth Hi-C maps*

Image quality evaluation

This section evaluated the quality of predicted Hi-C maps using the Fréchet Inception Distance FID, which measures similarity between real and predicted images by comparing the statistical distributions (mean and covariance) of their feature embeddings (Methods). C.Origami, ChromaFold, and GRACHIP produced blurred or low-contrast maps, reflected in high FID scores exceeding 20. In some cases, trained cell lines even yielded higher FID values than unseen ones, consistent with these models' optimization for numerical rather than perceptual accuracy.

By contrast, Epiphany and HiCDiffusion achieved significantly better image quality. Epiphany consistently produced the lowest FID scores, which means near-realistic reconstruction of experimental Hi-C maps. HiCDiffusion achieved intermediate performance (FID around 10), due to its generative diffusion process. Overall, the GAN-based Epiphany generated the most visually accurate and biologically plausible contact maps (Figure 6).

Downstream analysis: loop detection

Chromatin loop detection was used to evaluate the biological relevance of the predicted Hi-C maps. Chromatin loop detection is a downstream Hi-C analysis task that aims to identify specific long-range point-to-point interactions between genomic loci, which appear as focal enrichment “dots” above the local background in Hi-C contact matrices. These loops often reflect structural or regulatory interactions, such as enhancer–promoter contacts mediated by architectural proteins (e.g., CTCF/cohesin), therefore provide a biologically meaningful readout of chromatin organization. To evaluate whether predicted Hi-C maps preserved such biologically relevant features, four loop-calling tools, LASCA [23], HiCCUPS [24], SIP [25], and Mustache [26], were applied to both experimental and predicted maps.

Functional evaluation of loop detection across models and loop-caller tools

To assess the biological relevance of the detected chromatin loops, loop anchors were compared with independent transcriptional regulatory evidence from three complementary external resources. Curated transcription factor (TF)–target regulatory interactions were obtained from CollecTRI [34], which compiles literature-supported regulatory relationships. Functional downstream targets of TF perturbation were retrieved from KnockTF 2.0 [36], a database of gene expression changes following TF knockdown or knockout experiments. Direct TF–DNA binding evidence was obtained from ChIP-Atlas [35] using ChIP-seq datasets specific to the K562 cell line. These datasets represent distinct levels of regulatory support: CollecTRI provides prior knowledge of regulatory interactions, KnockTF captures functional effects of TF perturbation, and ChIP-Atlas provides cell-type-specific physical TF binding.

337 Rather than claiming direct causality, we evaluated whether predicted chromatin loops were
338 supported by any of these independent regulatory evidences.A loop was considered biologically
339 supported when at least one anchor overlapped a TF binding site (ChIP-Atlas), a TF-regulated gene
340 (KnockTF), or a curated TF–target interaction (CollecTRI). This integration enabled both quantification
341 of loop recovery and assessment of their potential functional relevance. (Methods).

342 **Table 2: Results of loop detection for each model and specified tools in cell line K562.**

Model	Loop calling tool	Total loops	Enhancer-promoter loops (% of total)	CollecTRI (% of total)	ChIP-Atlas (% of total)	KnockTF (% of total)
C.Origami	SIP	13758	3277 (23.8%)	1519 (11.0%)	2971 (21.5%)	898 (6.5%)
	LASCA	43304	8099 (18.7%)	3538 (8.1%)	7228 (16.6%)	1841 (4.3%)
	Mustache	11891	2789(19.9%)	1014(8.5%)	2177(18.3%)	571 (4.8%)
	HICCUPS	2489	776 (31.1%)	334 (13.4%)	740 (29.7%)	259 (10.4%)
Epiphany	SIP	9370	1589 (16.9%)	694 (7.4%)	1422 (15.1%)	317 (3.4%)
	LASCA	93574	9986 (10.6%)	3804 (4.0%)	8537 (9.1%)	1504 (1.6%)
	Mustache	5515	1425 (25.8)	680 (12.3%)	1341 (24.3%)	426 (7.7%)
	HICCUPS	2664	756 (28.3%)	349 (13.1%)	728 (27.3%)	249 (9.3%)
HiCDIffusion	SIP	20823	2390 (11.4%)	1018 (4.8%)	1969 (9.4%)	369 (1.8%)
	LASCA	111045	7414 (6.6%)	2676 (2.4%)	6018 (5.4%)	983 (0.9%)
	Mustache	10617	1808 (17.0%)	793 (7.4%)	1588 (14.9%)	403 (3.8%)
	HICCUPS	4250	469 (11.0%)	115 (2.7%)	397 (9.3%)	65 (1.5%)
ChromaFold	SIP	1220	528 (43.2%)	310 (25.4%)	525 (43.0%)	319 (26.1%)
	LASCA	18000	1738 (9.6%)	636 (3.5%)	1561 (8.6%)	300 (1.7%)
	Mustache	4693	1281 (27.2%)	657 (13.9%)	1227 (26.1%)	493 (10.5%)
	HICCUPS	134	48 (35.8%)	29 (21.6%)	46 (34.3%)	38 (28.4%)
GRACHIP	SIP	4065	468 (11.5%)	194 (4.7%)	388 (9.5%)	63 (1.5%)

	LASCA	3844	422 (10.9%)	164 (4.2%)	349 (9.0%)	62 (1.6%)
	Mustache	703	91 (12.9%)	29 (4.1%)	84 (11.9%)	16 (2.3%)
	HICCUPS	22	2 (9.1%)	0 (0.0%)	2 (9.1%)	0 (0.0%)
True HiC	SIP	7846	1823 (23.2%)	827 (10.5%)	1768 (22.5%)	496 (6.3%)
(ground	LASCA	194086	14855 (7.6%)	5226 (2.6%)	12020 (6.1%)	1868 (1.0%)
truth)	Mustache	8871	2388 (26.9%)	1098 (12.3%)	2303 (25.9%)	700 (7.9%)
	HICCUPS	3513	1145 (32.5%)	499 (14.2%)	1130 (32.1%)	370 (10.5%)

As expected, loops detected from true Hi-C data showed the highest counts and served as the reference set (Table 2). Among predicted contact maps, Epiphany and C-Origami produced the largest number of loops, whereas GRACHIP detected substantially fewer, consistent with its lower structural accuracy. However, loop quantity did not directly correspond to biological support. Loops overlapping K562-specific TF binding sites from ChIP-Atlas were more frequent than those supported only by curated regulatory associations from CollecTRI, indicating that cell-type-specific binding provides stronger support for chromatin looping than general regulatory knowledge. This observation is consistent with established models in which chromatin loops are mediated by active transcription factors in a context-dependent manner.Several models recovered loops enriched for transcription factors known to be active in K562 cells, including CTCF, RAD21, and NKRF. CTCF and RAD21 are central architectural proteins involved in loop extrusion and maintenance of topologically associating domains, whereas NKRF functions as a transcriptional repressor of immune-related genes [27, 28]. Many predicted loops connected TF binding regions to nearby gene targets, including EIF4G2 and AP2A2 (NKRF-associated), SVIL (RAD21-associated), and SLIT1 and S1PR1 (CTCF-associated), which are relevant to hematopoietic cell function. Nevertheless, loops simultaneously supported by TF binding, regulatory association, and validated downstream targets were rare even in true Hi-C data, reflecting the stringent criteria required to define a functional regulatory chromatin interaction.

Among loop callers, LASCA detected the largest number of loops but exhibited limited overlap with regulatory evidence, suggesting high sensitivity but lower specificity. In contrast, Mustache and SIP detected fewer loops but a higher proportion of biologically supported interactions: approximately 25% overlapped K562-specific TF binding sites and 10% overlapped curated TF regulatory interactions, indicating improved biological precision. HiCCUPS, which relies on sharp focal interaction peaks, performed poorly on GRACHIP maps and detected only 22 loops.

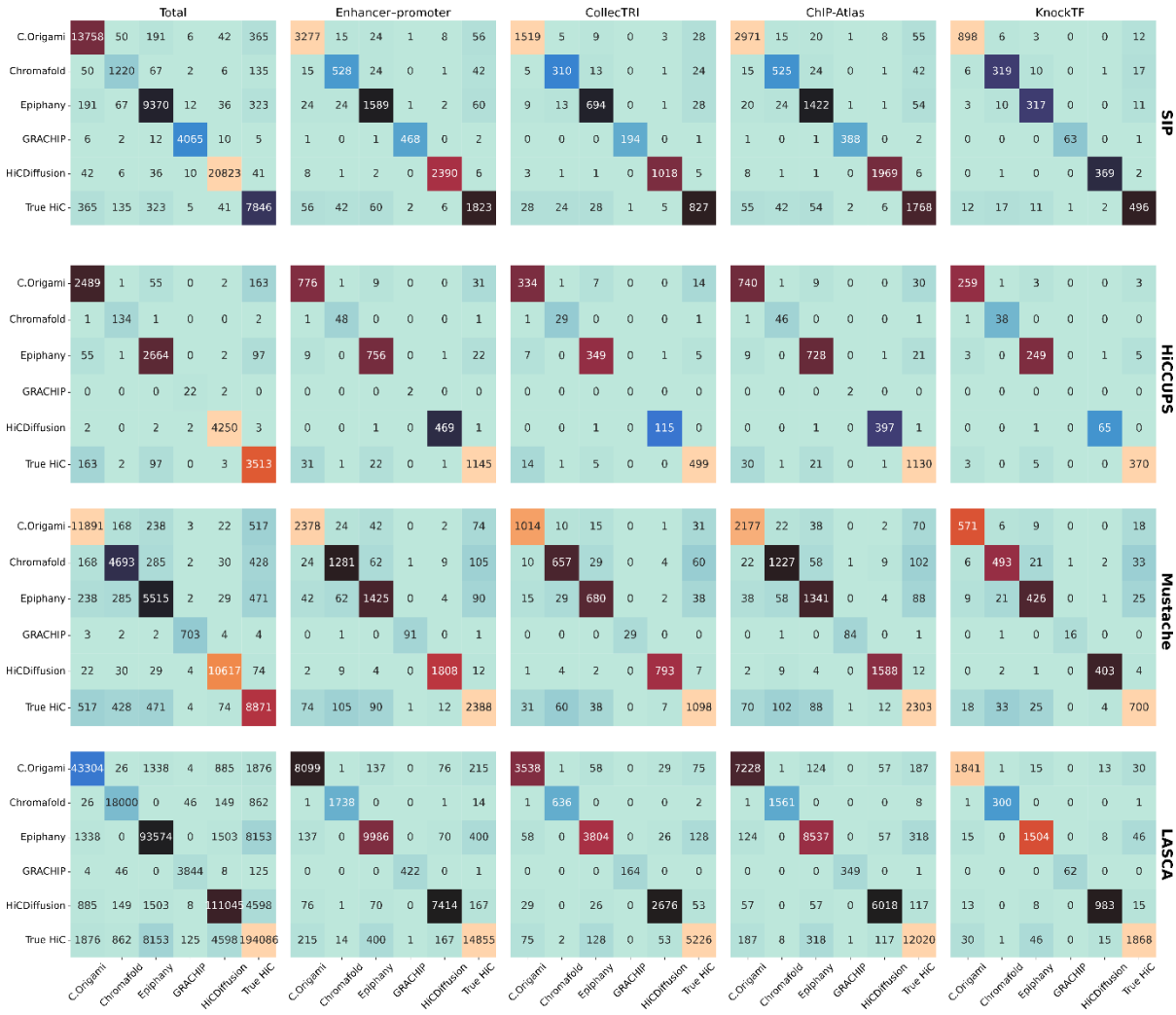


Figure 7: Loop overlap between five models and the true Hi-C map across different loop callers.

Cross-model loop overlap using individual loop caller.

The biological relevance of predicted Hi-C maps was evaluated by comparing chromatin loops identified from five prediction models against loops derived from the true Hi-C map. For consistency,

all loop calls were performed using the same loop-calling tool within each comparison. A loop was initially considered overlapping only if both of its anchors matched those of a loop in another dataset.

C.Origami and Epiphany consistently achieved the highest overlap between predicted biologically supported loops and loops derived from the real Hi-C map across most loop-calling tools (Figure 7). Epiphany's strong performance was expected given its high-resolution contact maps and high visual fidelity. Interestingly, C.Origami also performed well despite producing comparatively blurred contact maps and demonstrating limited generalization. This suggests that key latent chromatin interaction patterns were still preserved in C.Origami predictions, allowing loop callers, particularly LASCA and Mustache, to recover biologically meaningful interactions even from more diffuse signals. Therefore, visual sharpness alone was not sufficient to fully explain the biological utility of a predicted Hi-C map.

To quantify loop-calling performance, predicted loops were first compared to loops detected in the true Hi-C map. Loops present in both the predicted and true Hi-C maps were defined as true positives, loops detected only in the predicted map as false positives, and loops present only in the true Hi-C map as false negatives. Using these definitions, precision and recall were calculated for each combination of prediction model and loop-calling tool, and the results were summarized in a two-dimensional precision–recall space (Figure 8). In addition to structural agreement with the true Hi-C loops, we evaluated biological support using three independent regulatory evidence sources: curated TF–target interactions (CollecTRI), functional TF perturbation targets (KnockTF 2.0), and K562-specific TF binding sites (ChIP-Atlas).. Across all loop callers, Epiphany and C.Origami consistently ranked among the top-performing models in both precision and recall, indicating robust performance regardless of the loop-calling method used. ChromaFold showed more variable behaviour: it achieved high precision with SIP and obtained the best precision and recall among models when using Mustache, but performance dropped substantially when using other loop callers. Similar trends were observed when evaluating all detected loops and other categories of biologically supported loops

(Supplementary Figure S15). Collectively, these results indicate that Epiphany and C.Origami provide the most stable and reproducible performance across multiple loop-calling tools.

Despite these differences, it is important to note that absolute precision and recall values remained low across all models (both metrics typically < 0.15), indicating the inherent difficulty of recovering true chromatin loops from predicted contact maps. To complement structural accuracy, we evaluated the biological support of detected loops. For each loop caller, we calculated the proportion of detected loops whose anchors overlapped independent regulatory evidence from CollecTRI, KnockTF 2.0, or K562-specific ChIP-Atlas binding sites (Figure 9), This metric represents the fraction of predicted loops supported by known or functional regulatory interactions relative to the total number of loops detected, thereby distinguishing potentially functional loops from background structural detections. Using this measure, C.Origami and Epiphany exhibited distributions similar to those of the true Hi-C map across loop callers. This suggests that, although the exact overlap with the ground-truth loop set was limited, these models maintained a comparable ability to generate loops enriched for biological regulatory interactions. In other words, Epiphany and C.Origami produce fewer ground-truth-matching loops, but the loops they do enable are biologically meaningful at a rate comparable to real Hi-C, supporting their utility for downstream biological interpretation.

Cross-tool loop overlaps within each predicted model

Loop-calling tools also influenced overlap outcomes. HiCCUPS detected fewer overlapping loops due to its dependence on sharp signal peaks, whereas LASCA, Mustache, and SIP were more tolerant to noise and better captured biologically relevant structures. This highlighted the importance of using flexible, noise-resilient tools for analysing predicted Hi-C.

To better understand the behaviour of different loop-calling tools when applied to the same predicted Hi-C map, the overlap of loops identified by SIP, HICCUPS, LASCA, and Mustache within each individual model was evaluated (Supplementary Figure S14). The analysis revealed limited consistency across tools, only a small fraction of loops, particularly enhancer–promoter or TF-associated loops, were

shared by all four. Models producing higher-quality predictions, such as Epiphany and C.Origami, exhibited greater cross-tool agreement, indicating that more accurate structural reconstructions yielded more reproducible loop calls. In contrast, models with noisier outputs, like GRACHIP, showed minimal overlap due to inconsistent or spurious detections.

Among the tools, Mustache and SIP demonstrated the highest overlap, likely due to their shared computer vision–based algorithms that emphasize local spatial patterns. LASCA and HiCCUPS, though both clustering-based, differed in behaviour: LASCA detected the most loops but with low biological precision (only around 10% overlapped with known regulatory features), while HiCCUPS remained overly conservative at 10 kb resolution, missing many valid interactions. Biologically meaningful loops identified by three or more tools were rare but often involved enhancer–promoter pairs with TF binding, suggesting that multi-tool consensus loops were highly functionally relevant.

In addition, as shown in Figure 9, HiCCUPS detected the fewest loops among the four tools, yet the fraction of loops overlapping known biological regulatory features was among the highest. This trend was observed not only for the ground-truth Hi-C map but also for most predicted contact maps (except for ChromaFold), with Mustache generally showing the next best performance. This pattern was consistent with previous reports indicating that both HiCCUPS and Mustache performed robustly at 10 kb resolution, where their detection strategies tended to prioritise high-confidence interactions [29]. Interestingly, ChromaFold showed a distinct behaviour: although HiCCUPS and Mustache still yielded high biological precision, SIP consistently achieved the best performance in most cases. Moreover, the fraction of biologically supported loops in ChromaFold was unexpectedly comparable to, or even higher than, that observed in the ground-truth Hi-C map, despite ChromaFold producing fewer loops than true Hi-C and fewer than other high-performing models such as Epiphany and C.Origami. These results suggested that ChromaFold tended to produce a smaller set of loop candidates, yet this set was preferentially enriched for biologically supported interactions and reproducible across loop-calling methods.

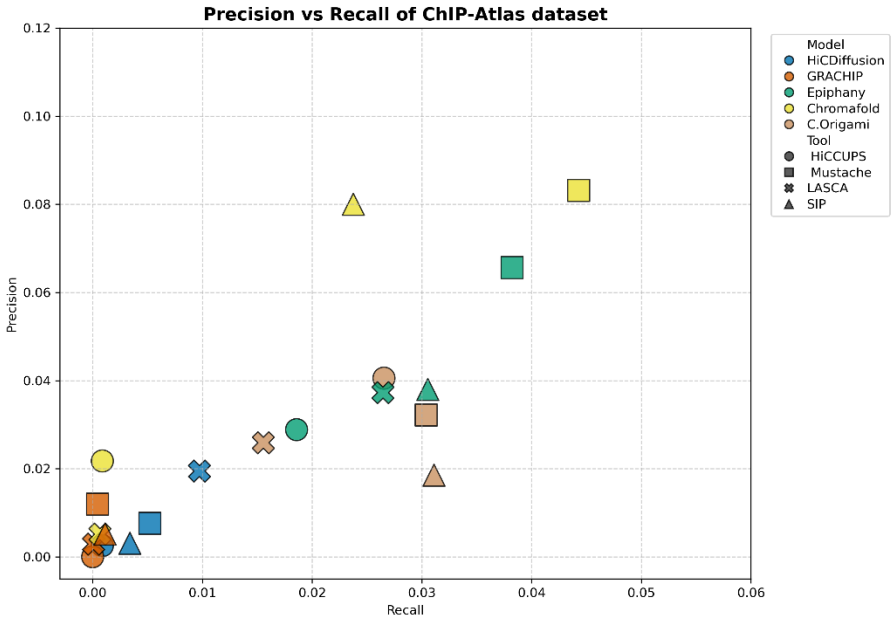


Figure 8: Precision–recall analysis of chromatin loops supported by ChIP-Atlas dataset. *The y-axis indicates precision, and the x-axis indicates recall, using loops derived from the true Hi-C map as the ground truth reference. Each marker represents one combination of a Hi-C prediction model and a loop-calling tool. Marker colour denotes the prediction model, while marker shape denotes the loop caller.*

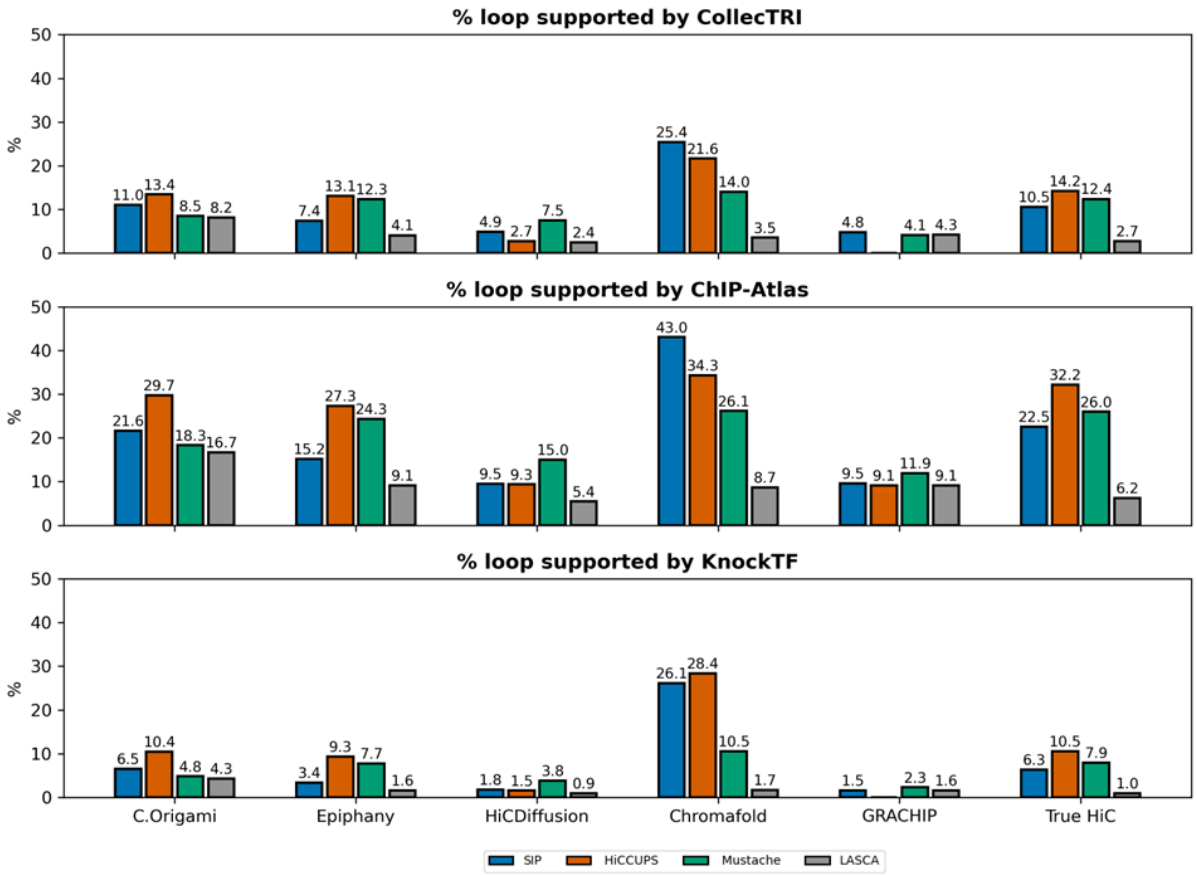


Figure 9: Percentage of biologically supported loops among all detected loops across models and loop callers. *The y-axis represents the percentage of biologically supported loops relative to the total number of detected loops. Each panel contains six groups of bars, corresponding to the five prediction models and the true Hi-C map. Bar colour indicates the loop-calling tool used to detect loops.*

3. Discussion

Summary of model characteristics

In this manuscript, five deep learning models, C.Origami, Epiphany, HiCDiffusion, ChromaFold and GRACHIP, were systematically evaluated for their ability to predict Hi-C contact maps and recover biologically meaningful chromatin features, such as loops. These models differed in their architectures, input modalities, and training strategies, resulting in variable performance in prediction accuracy, generalizability, image quality, and biological interpretability. For clarity, each model was compared based on five key aspects: prediction accuracy, generalization across cell lines, input type (single-omic

or multi-omics), visual quality of contact maps, and capacity to detect chromatin loops, particularly enhancer–promoter interactions.

C.Origami demonstrated high accuracy in the cell line on which it was trained [21]; however, its performance dropped markedly when applied to unseen cell types, indicating limited generalizability. The model integrates genomic sequence with epigenomic features such as ATAC-seq and CTCF binding. Ablation analysis further revealed a strong dependence on the CTCF track, while other modalities contributed less. Although the visual quality of its predicted maps was relatively low and appeared blurred, the model still captured relevant biological patterns, particularly for loop detection. This observation is consistent with the original study, which identified CTCF as a key determinant of genome organization and loop formation. Accordingly, despite blurred contact maps, C.Origami recovered biologically meaningful chromatin structures, including CTCF–CTCF and promoter–enhancer loops.

Epiphany showed strong and balanced performance and generalized well to new cell types. This agrees with the original study, which specifically designed the model to overcome the limitation of sequence-only predictors that fail to generalize across cell types [18]. The model uses multiple epigenomic tracks, including DNase/ATAC-like accessibility, CTCF, and histone modifications such as H3K27ac, enabling it to capture cell-type-specific chromatin organization. By incorporating a GAN-based framework, Epiphany produced visually sharp contact maps that closely resembled experimental Hi-C data. Consequently, Epiphany performed well in detecting both general and biologically supported loops. One limitation, however, is its restricted window size of 1 Mb, which allows detection of interactions up to this distance but may miss longer-range interactions.

HiCDiffusion, which uses only genomic DNA sequence as input, performed surprisingly well [17]. However, sequence-based prediction inherently lacks cell-state information, and prior studies have shown that sequence-only models tend to predict similar structures across cell types because DNA sequence does not encode dynamic regulatory states. The diffusion-based generative framework primarily improves visual quality by reducing blurring in predicted heatmaps and optimizing image

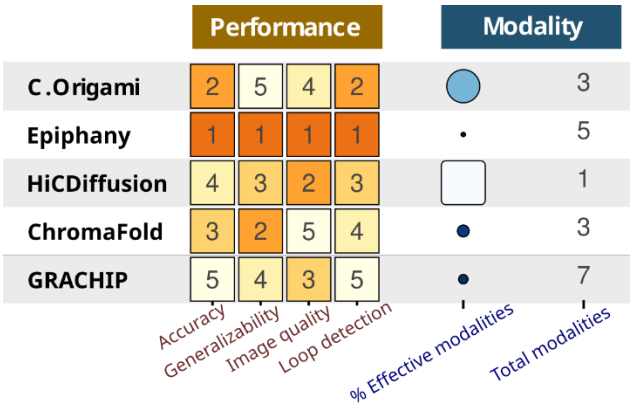
realism, as reflected by improvements in the FID. Therefore, although HiCDiffusion produced visually clear maps, its biological specificity should be interpreted cautiously.

ChromaFold achieved moderate accuracy but showed good cross-cell-type generalization. Unlike C.Origami and Epiphany, it relies primarily on single-cell chromatin accessibility and CTCF motif information rather than multiple bulk epigenomic assays [19]. The original study demonstrated that co-accessibility between accessible regions reflects chromatin looping events and enables prediction of cell-type-specific interactions. Previous benchmarks also reported performance comparable to C.Origami and even improved performance when appropriate CTCF information was included. Our ablation results, showing a strong dependence on co-accessibility features, are consistent with this interpretation. The model's lighter architecture and reduced modality requirements may also reduce overfitting relative to heavily parameterized multi-omics models. Although the predicted maps appeared blurred and the visual quality was limited, ChromaFold was still able to recover chromatin loops, including both general and context-specific interactions.

GRACHIP showed weaker predictive performance in our evaluation despite being designed to improve generalization. The model incorporates DNA sequence, ATAC-seq, and CUT&RUN-derived regulatory features, including CTCF and histone marks, and additionally encodes prior chromatin interaction intensity using a graph neural network [20]. The authors proposed that incorporating interaction relationships would enhance cross-cell-line prediction; however, they also noted that many predictive models, including C.Origami, exhibit performance variability across different cellular contexts. Our results suggest that although the graph-based representation may help capture interactions, it did not translate into improved Hi-C reconstruction accuracy or loop recovery in this benchmark setting.

We summarized the ranking performance of each model across four evaluation categories: accuracy, generalizability, visual quality, and loop detection (Figure 10). Overall, Epiphany ranked highest across all evaluation criteria. C.Origami performed strongly in accuracy and loop detection but showed poor generalization across different cell types. Despite relying only on genomic DNA sequence, HiCDiffusion

514 achieved moderate performance in both generalizability and loop detection. ChromaFold showed
515 consistently moderate performance across all categories, whereas GRACHIP demonstrated the lowest
516 overall performance despite using the largest number of input modalities.



517

518 **Figure 10: Summary of the evaluation characteristic of each chromatin contact prediction model.**
519 *Accuracy was ranked based on the average values of two biological metrics, insulation score*
520 *correlation and observed/expected (O/E) correlation, calculated across the training cell lines.*
521 *Generalizability was evaluated using the same metrics averaged across previously unseen cell lines.*
522 *Visual quality was ranked according to the average FID values across all cell lines. Loop detection*
523 *performance was determined by the number of biologically meaningful loops predicted by each model*
524 *relative to the ground truth Hi-C map, averaged across all loop-calling tools. The number of input omics*
525 *modalities used by each model was also summarized, together with the proportion of modalities*
526 *contributing measurably to performance, referred to as the "% effective modalities.*

527 **Insights from the comparative analysis**

528 From the comparison, several key insights emerged. More input modalities did not necessarily
529 guarantee better performance. Multi-omic models often learned disproportionately from one
530 dominant signal, typically CTCF, while neglecting others , as shown by the ablation analysis in Figure 5
531 and Supplementary Figure 3-15, where removal of the CTCF track produced the largest performance
532 decrease compared with other modalities. HiCDiffusion, despite using only genomic sequence,

performed comparably or even better than some multi-omic models, demonstrating the importance of model architecture and training strategy over the number of input features.

CTCF was a critical input feature across models [30]. As a central player in organizing 3D chromatin architecture, CTCF defined loop anchors and TAD boundaries [24]. Models incorporating experimentally measured CTCF binding generally achieved improved structural reconstruction, particularly for boundary and loop features. However, previous studies also noted that CTCF alone is insufficient to capture cell-type-specific chromatin organization. Additional regulatory context, such as histone modifications or co-accessibility between regulatory elements, was often required to recover accurate and biologically meaningful interaction patterns. Thus, while CTCF provides essential structural information, effective Hi-C prediction depends on combining it with complementary regulatory signals rather than relying on it as a single determinant of genome architecture.

As noted above, many models incorporate multiple input modalities, yet only a subset of these signals substantially influences performance. This suggests that current architectures may not fully exploit the available information and may introduce unnecessary complexity. Future work should therefore focus on developing approaches that more effectively integrate complementary regulatory signals and balance model complexity with informative input features. Improving how modalities are utilized may enhance both prediction robustness and biological interpretability.

MSE proved to be a limited evaluation metric. It did not adequately capture biological relevance or map quality and was highly dependent on model architecture and loss function. For example, models that directly optimized MSE (e.g., C.Origami) often showed artificially low error on training data, while models using adversarial or generative losses (e.g., Epiphany, HiCDiffusion) exhibited higher MSE despite producing biologically realistic and visually accurate maps. Therefore, MSE alone was insufficient to judge model performance. Although MSE is widely used in general machine learning applications, it was not commonly adopted for evaluating Hi-C prediction models. Among the reviewed models, only a few, such as C.Origami, used MSE to assess accuracy, primarily for internal comparisons

558 within the model rather than across different models [29]. In C.Origami's case, MSE was supplemented
559 with additional evaluation methods, including insulation-based metrics and correlation-based
560 measures, to better reflect biological relevance. In contrast, most comparative studies between
561 models, such as those involving HiCDiffusion vs C.Origami, GRACHIP vs C.Origami, or Epiphany vs Akita,
562 generally avoided MSE altogether. Instead, they focused on metrics more informative for assessing
563 biological and structural fidelity [17], [18], [20]. These typically included correlation-based metrics,
564 such as Pearson and Spearman correlation coefficients, which measured linear and rank-based
565 similarities between predicted and experimental Hi-C matrices, respectively. Other frequently used
566 metrics assessed the ability of models to replicate distance-dependent decay patterns in Hi-C data,
567 such as the O/E ratio and stratum-adjusted correlation coefficient (SCC), which controlled for genomic
568 distance effects [31]. Additionally, metrics based on higher-order chromatin structures, including
569 insulation score correlation and TAD boundary recovery rate, were employed to evaluate the accuracy
570 of TAD predictions [32]. In this study, we employed not only MSE but also two biologically meaningful
571 evaluation strategies: distance-dependent decay analysis using O/E correlation and TAD-level
572 evaluation using insulation score correlation. Further refinement could include metrics like the
573 stratum-adjusted correlation coefficient or distance-specific correlation measures, which offer a more
574 nuanced understanding of how well predicted contact maps reflect the complex spatial organization
575 of the genome.

576 Another important consideration was that the models evaluated in this study were originally trained
577 on different cell lines. This was done deliberately to maintain fidelity to the original versions of each
578 model, those published and made available for inference. Although model retraining was conducted,
579 this step was intended solely to verify that the code executed properly. By using the same training cell
580 lines specified in the original publications, we were able to reproduce and validate the models'
581 reported accuracies, ensuring that the retrained models functioned correctly. Although we adhered to
582 the original training cell lines for each model, the specific samples used during inference differed from
583 those used during training. For a fair comparison, we should standardized the input data across all five

models, using the same samples for each cell line during evaluation. Therefore, a limitation of this approach was that it introduced some inconsistencies in the comparison. Notably, ChromaFold, was trained on two cell lines, unlike the others which used a single training cell line. This raised questions about whether ChromaFold's performance was attributable to its model architecture or to the broader diversity of its training data. It also prompted consideration of whether training on multiple cell lines improved generalizability across cell types. Despite this limitation, the primary aim of this study was to compare the models as tools, that is, to assess the performance of the published, pre-trained versions that were ready for immediate use, rather than retraining all models under standardized conditions. Modifying the training data to unify cell lines across models could have compromised this objective by producing results based on altered versions of the original tools. However, in the future, if the focus shifts to evaluating the architectural advantages of each model while addressing concerns about differences in training datasets, it would be appropriate to retrain all models using the same cell line and dataset to enable a more controlled and interpretable comparison.

Finally, the performance of the same deep learning model varied across different chromosomes. For example, the prediction accuracy tended to fluctuate across the 22 chromosomes, with some chromosomes showing peaks in performance while others exhibited noticeable decreases. Interestingly, in the same model, this trend was almost consistent across four different cell lines: H1, GM12878, IMR90, and K562, despite their biological differences. Even when using five different models, all trained on different chromosomes or cell lines, a similar performance pattern was observed. Specifically, a drop in prediction accuracy was consistently seen on chromosomes 9, 15, and 22 across all models and cell lines. This consistent decrease suggested that chromosomes 9, 15, and 22 presented unique challenges for generalization and prediction, regardless of the model architecture or training data. There were several potential biological and technical explanations for this observation. First, chromosome size may play a role. Smaller chromosomes, such as chromosome 22, contains fewer genomic loci and thus generated fewer interaction pairs in Hi-C data [33]. This results in sparser contact maps, which were more difficult for models to learn and accurately predict. Second,

610 the structural complexity of certain chromosomes may affect performance. For instance,
611 chromosomes 9 and 15 are known to contain complex repetitive regions and were hotspots for
612 chromosomal translocations [34]. These structural variations lead to mapping ambiguities and reduced
613 the quality of Hi-C signals, making it harder for models to learn consistent patterns. Third, chromatin
614 interaction also varies across chromosomes: gene-rich chromosomes have denser transcriptional
615 activity and more regulatory interactions, whereas gene-poor chromosomes exhibit sparser patterns
616 [8]. If a model is trained on more chromosomes with rich regulatory interactions and then tested on
617 chromosomes with sparse or fundamentally different interaction landscapes, performance can drop
618 due to poor generalization. These differences directly affect Hi-C signal patterns and may influence
619 how easily a model can learn and generalize across chromosomes. In addition, variability in sequencing
620 depth, differences in chromatin organization (such as TADs and compartments), and uneven
621 distribution of epigenomic features like CTCF binding sites and histone modifications might also
622 contribute to performance differences across chromosomes. Taken together, these findings indicate
623 that both biological properties and technical factors influenced model performance across
624 chromosomes in our benchmark, consistent with known variability in Hi-C data and chromatin
625 organization.

626 **Loop detection from predicted Hi-C map**

627 Loop detection represents an important biologically meaningful downstream application of predicted
628 Hi-C contact maps. Although the evaluated prediction models operated at a relatively coarse resolution
629 (around 10 kb), many were still able to recover biologically relevant interactions, including enhancer–
630 promoter loops and TF-associated chromatin contacts. Nevertheless, precision and recall values
631 remained low when predicted loops were directly compared with loops derived from the true Hi-C
632 map. This limited performance is expected for several reasons. First, prediction errors in contact
633 intensity and local structural patterns can introduce noise, resulting in inconsistent loop detection
634 across callers. Second, the 10 kb resolution itself imposes a fundamental constraint: at this scale, fine

chromatin features, particularly short-range or tightly localized interactions, may be blurred, merged, or lost entirely. In addition, resolution mismatch and boundary uncertainty complicate the mapping of loop anchors between predicted and true Hi-C, further reducing apparent overlap even for biologically related interactions. These results indicate that resolution remains a major limiting factor for accurate loop recovery from predicted contact maps. Future work should investigate whether prediction models can be trained to generate higher-resolution contact maps (e.g., 5 kb or 2 kb) and whether improved resolution directly translates into more accurate and reproducible loop detection. Alternatively, post hoc resolution enhancement approaches, such as Hi-C super-resolution or refinement algorithms, may provide a practical strategy to convert 10 kb predictions into higher-resolution maps that better support downstream loop-calling analyses.

Another consideration is the choice of the loop-calling tool. Predicted maps often contained noise, blur, or artifacts do not present in real Hi-C data. Some tools, like HICCUPS, which were sensitive to sharp peaks and clean signals, performed poorly on predicted maps. In contrast, tools based on computer vision (e.g., Mustache, SIP) showed more robust performance, likely because they could tolerate visual noise and still detect relevant patterns [29]. Similar observations have been reported in recent loop-detection studies, where algorithm performance depends strongly on signal quality and map resolution. These results suggest that loop-caller effectiveness depends not only on algorithmic design but also on the statistical properties and visual structure of the input contact maps.

Finally, the structural quality of the predicted contact maps appeared to be more important than the specific choice of loop-calling tool. When a predicted contact map closely resembled the ground truth Hi-C map in both structural and biological content, as was observed with models like Epiphany and HiCDiffusion, most loop callers, including sensitive ones like HICCUPS, were able to effectively detect chromatin loops. This indicates that, under high-quality input conditions, different loop-calling algorithms tend to converge on similar biologically meaningful interactions.

However, an important exception was observed for C.Origami. Although C.Origami was not explicitly optimized to improve the visual realism of predicted contact maps, it still performed strongly in loop detection. Specifically, its overall loop-calling performance was consistently second only to Epiphany and exceeded that of HiCDiffusion, while also producing a substantial number of biologically supported loops overlapping those derived from true Hi-C. Notably, C.Origami enabled recovery of a relatively large number of loops consistently across multiple loop callers, including conservative tools such as HiCCUPS, indicating that its predicted contact maps retained sufficient structural signal for robust loop identification. These results indicate that perceptual image quality alone does not determine downstream biological utility. Instead, loop callers may be robust to certain forms of visual blurring, as long as key latent chromatin structures and interaction patterns are preserved.

This insight also raises an important question: between prediction accuracy and visual quality of Hi-C maps, which factor contributed more significantly to the final map quality that supported reliable loop detection? In this study, it was difficult to disentangle the effects of these two factors, as Epiphany demonstrated high performance in both aspects: achieved strong accuracy metrics, generated visually high-quality maps, and showed greater overlap with true biological loops. As Epiphany combined accurate prediction with GAN-based refinement that improved map sharpness, the independent contribution of visual quality to loop-calling outcomes could not be determined. Future work could address this by comparing model variants with and without visual refinement, for example, evaluating Epiphany with and without GAN refinement using identical loop-calling pipelines, to determine whether improved image quality alone enhances biological discovery.

4. Conclusion

In conclusion, we compared five deep learning models for Hi-C map prediction using datasets from four cell lines. Evaluation focused on prediction accuracy, visual quality, and loop detection. Ablation analysis examined the contribution of each input modality, revealing that CTCF is a key feature for accurate Hi-C map prediction. While most models used multiple modalities, only a few strongly

influenced performances. Among all models, Epiphany performed consistently well across all criteria, demonstrating high accuracy, generalizability, visual quality, and effective loop detection.

5. Methods

Data and cell line selection

This study used publicly available datasets from four well-characterized human cell lines: K562, IMR-90, GM12878, and H1-hESC, which were chosen for their extensive publicly available multi-omics data and obtained from the ENCODE and 4DN databases (Supplementary Table S1). IMR-90, GM12878, and H1-hESC were included in the training data of at least one evaluated model, whereas K562 was not. This allowed assessment of model performance on both seen and unseen cell types, providing insight into their generalization ability. Furthermore, the study only used 22 chromosomes for each cell line, excluding sex chromosomes.

The input data used for Hi-C contact map prediction included genomic DNA sequence and various epigenomic data. All genomic sequences were aligned to the hg38 human reference genome. Epigenomic data comprised chromatin accessibility (ATAC or DNase), CTCF binding, and histone modifications such as H3K4me3, H3K27ac, H3K4me1, and H3K27me3 (all by ChIP-seq).

Deep learning models for comparison

This study used five advanced deep learning models for the prediction of Hi-C contact maps: C.Origami, Epiphany, HiCDiffusion, ChromaFold, and GRACHIP. These models collectively represent a broad range of contemporary deep learning approaches, including CNNs, transformers, recurrent neural networks (RNNs) graph convolutional networks (GCNs), as well as generative techniques such as generative adversarial networks (GANs) and diffusion-based models.

All models were executed using the authors' publicly available implementations. The software was installed in a Python (3.11) environment with PyTorch as the primary deep learning framework, along with the dependencies specified in each repository. Training was performed on the Ghent University

708 high-performance computing (UGent HPC) cluster using GPU acceleration (NVIDIA GPUs), while
709 inference and downstream analyses were carried out on CPU nodes. Model parameters and
710 preprocessing steps followed the recommendations of the original publications unless otherwise
711 stated.

712 **C.Origami** [21] predicts Hi-C contact maps by integrating genomic and epigenomic information (hg38),
713 using three inputs: DNA sequence, CTCF binding, and ATAC-seq chromatin accessibility. The genomic
714 sequence was provided in FASTA format and one-hot encoded into five channels (A, T, C, G, and N),
715 which remained constant across all cell types. The ATAC-seq and CTCF data were pre-processed with
716 the Seq-N-Slide pipeline (https://igordot.github.io/sns/) to align raw FASTQ reads, remove low-quality
717 sequences, and produce normalized bigWig signal tracks. These signals were log-transformed to
718 reduce noise and ensure numerical stability before being used as input. The Hi-C training data were
719 processed at 10 kb resolution and downsampled to 8,192 bp to match the model's output format, with
720 a reversible natural logarithm transformation applied to stabilize training. The model architecture
721 consisted of two main components: feature extraction and contact map prediction. The feature
722 extraction stage included two one-dimensional convolutional encoders that captured local genomic
723 patterns, followed by a transformer module that modelled long-range dependencies. The transformer,
724 adapted from the BERT architecture, contained eight attention layers with 256 hidden units and eight
725 attention heads, using relative positional embeddings to encode genomic distance. Each input covered
726 a 2.1 Mb genomic region divided into 256 bins and contained seven channels: five from DNA sequence
727 and two from ATAC-seq and CTCF signals. After feature extraction, the transformer output was pairwise
728 concatenated to generate a 256 × 256 × 256 tensor, which was then decoded through five dilated
729 residual blocks to produce a 256 × 256 contact matrix representing predicted chromatin interaction
730 intensities at 8,192 bp resolution. The model was trained using MSE loss on the IMR-90 cell line, with
731 all chromosomes except 10 and 15 used for training; Chromosome 10 served as validation and
732 Chromosome 15 as the test set.

Epiphany [18] predicted Hi-C contact maps from epigenomic data representing 3D genome organization, using DNase I hypersensitivity, CTCF binding, and three histone marks (H3K4me3, H3K27ac, and H3K27me3). All input data were processed as described in the original method paper through a unified pipeline in which replicate BAM files for each modality were merged and converted into bigWig signal tracks using the bamCoverage tool with a 10 bp bin size and RPGC normalization to ensure consistent signal intensity across samples. The Hi-C training data were processed at 10 kb resolution and normalized using Hi-C-DC+, which applied a negative binomial regression model to compute observed-over-expected interaction ratios while accounting for genomic distance, GC content, and restriction fragment size. These normalized interaction values served as the model's training targets. Epiphany employed a sliding window approach in which each 1 Mb stripe of the contact matrix was predicted using a 1.4 Mb window of input signals, including 200 kb of padding on both sides. During training, the model predicted 200 consecutive stripes per forward pass, corresponding to an input tensor of size 5 channels × 3.4 Mb × 200 stripes, with a 10 kb stride between windows. The model architecture was based on a GAN consisting of a generator and discriminator. The generator contained multiple convolutional layers for local feature extraction followed by a bidirectional LSTM layer to capture long-range dependencies across stripes, producing realistic contact map predictions through a final fully connected layer. The discriminator, composed of convolutional layers, enforced an adversarial objective to distinguish real from generated maps. The convex combination of MSE and GAN losses enhanced prediction accuracy and structural realism. Epiphany was trained on the GM12878 cell line, with chromosomes 3, 11, and 17 held out for validation and testing to assess generalization.

HiCDiffusion [17], unlike multimodal models that integrated epigenomic data, relied solely on sequence features derived from the hg38 human reference genome, excluding telomeric and centromeric regions to avoid repetitive and noisy sequences. The model took a 2,097,152 base-pair (2 Mb) genomic window as input, one-hot encoded into five channels representing A, T, C, G, and N bases. Each input corresponded to a predicted Hi-C contact matrix of 256 × 256 bins at 8,192 bp resolution.

759 The architecture followed a two-stage transfer learning framework composed of a pretrained encoder-
760 decoder backbone and a diffusion-based refinement process. The encoder compressed the 2 Mb
761 sequence into 256 bins with 256 feature channels using convolutional layers, residual connections,
762 batch normalization, and ReLU activations, followed by a transformer module with eight attention
763 heads to capture long-range dependencies. The decoder employed dilated convolutions to reconstruct
764 an initial 256 × 256 single-channel contact map, which served as the base prediction. This pretrained
765 encoder–decoder was then integrated into a diffusion refinement stage, where a U-Net denoising
766 network iteratively learned to remove Gaussian noise added to the predicted maps. During training,
767 the model minimized reconstruction error by progressively denoising corrupted contact maps, and
768 during inference, it started from random noise and refined it through learned iterative denoising steps
769 guided by the encoder–decoder features. This approach enabled the generation of visually realistic
770 and structurally coherent contact maps. HiCDiffusion was trained on the GM12878 cell line and used
771 all autosomal chromosomes except Chromosome 22 for testing and Chromosome 21 for validation.

772 **ChromaFold** [19] used single-cell chromatin accessibility data with CTCF motif scores to predict HiC
773 contact map data. The model leveraged two major features derived from scATAC-seq data: pseudobulk
774 chromatin accessibility and co-accessibility profiles. Pseudobulk accessibility was generated by
775 aggregating single-cell accessibility signals across a population of cells to provide a robust
776 representation of overall chromatin openness. To address the sparsity of scATAC-seq data, metacells,
777 clusters of similar cells, were constructed, and co-accessibility between genomic regions was
778 quantified using the Jaccard similarity of binarized accessibility profiles across metacells, enabling the
779 model to capture interaction patterns at a population level. The CTCF motif score track was computed
780 by scanning genomic DNA sequences with CTCF position weight matrices to identify potential binding
781 sites that contribute to chromatin looping and domain organization. The Hi-C training data were
782 processed at 10 kb resolution and normalized into Z-scores using HiC-DC+, with values clipped between
783 –16 and +16 to reduce the influence of outliers. ChromaFold's architecture consisted of two parallel
784 feature extractors: the first processed pseudobulk accessibility and CTCF motif score tracks through 15

convolutional layers to capture local context, while the second extracted interaction-specific features from co-accessibility data. Outputs from both extractors were concatenated and passed through a linear prediction layer that estimated contact strengths between a central genomic bin and its surrounding bins within a 2 Mb window, forming a V-shaped stripe prediction. The model was trained in two stages for improved convergence: first optimizing the primary extractor and temporary prediction head, then freezing the learned weights while training the co-accessibility branch and final layer. ChromaFold used 4.01 Mb input windows and was trained on IMR-90 and GM12878 cell lines, with chromosomes 3 and 15 reserved for validation and chromosomes 5, 18, 20, and 21 held out for testing.

GRACHIP [20], a graph-based deep learning model for predicting Hi-C contact maps, integrated 7 input modalities: genomic DNA sequences, ATAC-seq data, and five CUT&RUN-derived epigenomic features: CTCF, H3K4me3, H3K4me1, H3K27ac, and H3K27me3, based on the hg38 human reference genome. CUT&RUN data were processed through the 4DN pipeline, while ATAC-seq data followed the ENCODE ATAC-seq pipeline. Both pipelines generated normalized bigWig signal tracks as final outputs. For CUT&RUN, raw reads underwent quality control, adapter trimming, alignment with Bowtie2, and filtering to retain only high-quality, unique reads before producing bigWig tracks. Similarly, ATAC-seq reads were aligned, duplicates and mitochondrial reads were removed, and chromatin accessibility signals were output in bigWig format. DNA sequence data were processed using a pretrained DNABert model, which transformed nucleotide sequences into 768-dimensional embeddings that captured rich contextual information. Hi-C training data were processed with the 4DN Hi-C pipeline at 10 kb resolution, including alignment with BWA, filtering with pair tools, duplicate removal, and normalization of final contact matrices after merging biological replicates. GRACHIP's architecture combined three modules to model multi-scale genomic dependencies: a three-layer GCN to encode genomic features and structural relationships, a 12-layer Transformer with 12 attention heads to capture long-range dependencies, and a six-layer CNN to extract local interaction patterns. The model produced a 200 × 200 contact matrix representing predicted chromatin interactions within a 2 Mb

genomic window at 10 kb resolution. By integrating graph-based representations with sequence and epigenomic features, GRACHIP effectively modelled both linear and spatial genomic contexts. The model was trained on the H1 human embryonic stem cell line, using all chromosomes for training except chromosomes 10 and 15, which were reserved for evaluation.

Most models were unable to predict interactions across the entire length of a chromosome due to memory and computational constraints. Instead, predictions were made on fixed-size windows, commonly 2 Mb in length. Supplementary Table S2, S3, S4 summarize key information for each model, including the input modalities, resolution, cell lines used for training, the specific deep learning techniques employed in each architecture, and the source code of each model.

Overview of workflow

The workflow began with data collection and preprocessing. Each evaluated model required specific input modalities and preprocessing procedures. To ensure fair and reproducible evaluation, all models were retrained using the original preprocessing steps, input modalities, and training settings described in their original publications. The same cell line and chromosome splits were also maintained for training, ensuring that the retrained models produced results consistent with those originally reported. Following preprocessing, the prepared data were input into each model to generate predicted Hi-C contact maps across five human cell lines. During inference, the same preprocessing protocols were applied to maintain methodological consistency. The predicted contact maps were then compared with experimental Hi-C data from the corresponding cell lines. To assess prediction accuracy, the predicted contact maps were quantitatively compared against the ground truth Hi-C maps of the same cell lines. For image quality assessment, the Fréchet Inception Distance (FID) was used to evaluate the visual similarity between predicted and true contact maps. Finally, to evaluate the utility of the predicted maps in downstream tasks, both predicted and ground truth contact matrices were input into loop-calling tools. The resulting loops were compared to evaluate how well each model recovered biologically relevant chromatin interactions. While some original model studies examined

structural features such as loops or TADs, they typically relied on a single analysis strategy and did not systematically compare performance across multiple loop-calling algorithms. Here, we extended these approaches by applying several loop callers and directly comparing loop recovery, providing a more standardized assessment of downstream biological utility.

Evaluation criteria for model comparison

Accuracy performance

Model performance was evaluated by comparing predicted Hi-C matrices with experimentally derived contact maps using three quantitative measures: MSE, insulation score correlation, and observed-versus-expected (O/E) Pearson correlation. MSE quantifies the average squared difference between predicted and ground-truth contact frequencies. Insulation score correlation evaluates whether the model captures local chromatin domain organization (e.g., TAD boundaries) by computing insulation scores along the genome from both predicted and experimental matrices and comparing the resulting insulation profiles using Pearson correlation. Specifically, for each genomic bin, insulation scores are computed within a fixed window (≈500 kb) by summarizing average contacts in upstream, downstream, and central regions, and calculating the ratio $\frac{\max(upstream, downstream)+pseudocount}{central+pseudocount}$. Finally, O/E Pearson correlation measures global agreement after normalizing contact frequencies to account for distance-dependent decay, by flattening the observed/expected-normalized matrices and computing Pearson correlation. Before analysis, all matrices were log-transformed using $log_{10}(count + 1)$ to normalize data distributions. Comparisons were conducted separately for each chromosome and cell line to assess model robustness across biological contexts. Results were also compared between training and unseen cell lines to evaluate generalization. All performance metrics were summarized under identical conditions to enable direct model comparison.

Ablation testing

To assess the contribution of each input modality, we performed ablation testing by removing selected features and measuring the resulting change in performance. Unlike Epiphany, which retrained models after masking input tracks, we conducted post-training ablation: model parameters were fixed and removed inputs were replaced with neutral signals. This approach evaluates the model's dependence on each modality during inference rather than its ability to relearn without it, and also avoids the substantial computational cost and inconsistent training procedures across models. For sequence inputs, nucleotides were replaced with the ambiguous base "N." For epigenomic features (e.g., ATAC-seq or histone marks), signal values were set to zero while preserving genomic coordinates. Models with few input types (C.Origami and ChromaFold) were tested under all modality combinations, whereas models with more inputs were evaluated using single and grouped ablations. Modalities were grouped by biological function: (1) chromatin accessibility (ATAC-seq, DNase I), (2) transcription factor binding (CTCF), (3) activating histone marks (H3K4me3, H3K27ac, H3K4me1), and (4) repressive histone marks (H3K27me3). HiCDiffusion was excluded because it relies only on DNA sequence. Ablation analyses were performed on chromosomes 5, 6, 10, and 15 as representative genomic regions.

Image quality

Quantitative metrics alone cannot fully assess the perceptual realism of predicted Hi-C maps. Therefore, Fréchet Inception Distance (FID) was used to evaluate the visual quality of predicted Hi-C contact maps. FID is a standard metric for assessing generative models, including GANs and diffusion models, by comparing the distribution of generated images to that of real images in the feature space of a pretrained InceptionV3 network. Specifically, it fits multivariate Gaussian distributions to the extracted feature activations and computes the Fréchet distance between them based on their mean and covariance. Lower FID values indicate greater visual similarity to the experimental Hi-C maps.

Downstream loop detection analysis

To evaluate the biological utility of predicted Hi-C maps, downstream analysis focused on identifying chromatin loops associated with transcriptional regulation. Four loop-calling tools were used: LASCA [23], HiCCUPS [24], SIP [25], and Mustache [26]. Among these, LASCA and HiCCUPS were clustering-based methods, while SIP and Mustache applied computer vision techniques. Clustering-based tools used algorithms such as DBSCAN to detect loops by grouping nearby points based on spatial proximity and cluster size, with HiCCUPS identifying sharp focal peaks using a donut-shaped local background, and LASCA employing graph-based community detection to handle complex and sparse data. In contrast, computer vision methods analysed the Hi-C contact maps as images: Mustache detects loops using scale-space theory to identify peaks at multiple scales, and SIP integrates advanced image processing to identify loops and domains by recognizing spatial patterns. The reason for choosing these four tools was to evaluate how predicted Hi-C maps perform in loop detection using two different types of algorithms: clustering-based and computer vision-based methods. Within each category, we selected two tools to capture variation in loop detection sensitivity at different resolutions. HiCCUPS and Mustache were known to predict more loops at 10 kb resolution, while LASCA and SIP tended to detect more loops at higher resolutions like 5 kb [29]. Since the predicted Hi-C maps in this study have a 10 kb resolution, comparing these tools allows assessment of loop detection performance across different algorithms and resolution sensitivities.

For this analysis, loop calling is performed on the predicted and true Hi-C maps (converted into the required ".hic" format using juicer tool with KR normalization). The K562 cell line was chosen, as it was not included in model training, providing an unbiased test of generalization.

After loop calling, detected loops were annotated with enhancer and promoter regions. Enhancers were obtained from EnhancerAtlas 2.0 [35], and promoters were defined as ±2 kb around transcription start sites using GENCODE (GRCh38) annotations. To assess biological relevance, predicted loops were compared with three reference resources: CollecTRI [36], a curated database of transcriptional regulatory interactions; ChIP-Atlas [37], which provides transcription factor binding profiles; and

KnockTF 2.0 [38], which contains gene expression data following transcription factor knockdown or knockout. For the KnockTF dataset, differential expression analysis between TF knockdown and control samples was performed using the *limma* package, executed in Python via the rpy2 interface. Only statistically significant TF–target gene pairs (FDR < 0.05) were retained, and these pairs were mapped onto predicted chromatin loops to identify regulatory interactions supported by experimental evidence.

Finally, several comparisons were made:

(1) Total number of predicted loops compared to the ground truth loops from the reference Hi-C map.

(2) Overlap between enhancer-associated loops predicted by each model and true Hi-C loops.

(3) Overlap between predicted loops and curated TF–target regulatory interactions (CollecTRI).

(4) Overlap between predicted loops and transcription factor binding evidence (ChIP-Atlas). (5) Overlap between predicted loops and expression-supported TF–target relationships derived from KnockTF 2.0.

Results from all loop-calling tools were then compared to evaluate the performance of predicted Hi-C maps across different loop detection methods. This framework assesses whether predicted chromatin contacts are not only structurally plausible but also supported by independent regulatory and gene expression evidence.

6. Code availability

The code for this benchmark is at https://github.com/CBIGR/bulk_hic_benchmark.

References

[1] Y. F. Li and R. B. Altman, "Systematic target function annotation of human transcription factors," *BMC Biol*, vol. 16, no. 1, p. 4, Dec. 2018, doi: 10.1186/s12915-017-0469-0.

[2] H. Ray-Jones and M. Spivakov, "Transcriptional enhancers and their communication with gene promoters," *Cell. Mol. Life Sci.*, vol. 78, no. 19–20, pp. 6453–6485, Oct. 2021, doi: 10.1007/s00018-021-03903-w.

[3] H. Tao *et al.*, "Computational methods for the prediction of chromatin interaction and organization using sequence and epigenomic profiles," *Briefings in Bioinformatics*, p. bbaa405, Jan. 2021, doi: 10.1093/bib/bbaa405.

[4] L. Yao, B. P. Berman, and P. J. Farnham, "Demystifying the secret mission of enhancers: linking distal regulatory elements to target genes," *Crit Rev Biochem Mol Biol*, vol. 50, no. 6, pp. 550–573, Nov. 2015, doi: 10.3109/10409238.2015.1087961.

[5] K. Zhang *et al.*, "A single-cell atlas of chromatin accessibility in the human genome," *Cell*, vol. 184, no. 24, pp. 5985-6001.e19, Nov. 2021, doi: 10.1016/j.cell.2021.10.024.

[6] L. A. Lettice *et al.*, "A long-range Shh enhancer regulates expression in the developing limb and fin and is associated with preaxial polydactyly," *Hum Mol Genet*, vol. 12, no. 14, pp. 1725–1735, Jul. 2003, doi: 10.1093/hmg/ddg180.

[7] S. Smemo *et al.*, "Obesity-associated variants within FTO form long-range functional connections with IRX3," *Nature*, vol. 507, no. 7492, pp. 371–375, Mar. 2014, doi: 10.1038/nature13138.

[8] E. Lieberman-Aiden *et al.*, "Comprehensive Mapping of Long-Range Interactions Reveals Folding Principles of the Human Genome," *Science*, vol. 326, no. 5950, pp. 289–293, Oct. 2009, doi: 10.1126/science.1181369.

[9] B. R. Lajoie, J. Dekker, and N. Kaplan, "The Hitchhiker's guide to Hi-C analysis: Practical guidelines," *Methods*, vol. 72, pp. 65–75, Jan. 2015, doi: 10.1016/j.ymeth.2014.10.031.

[10] L. Chang *et al.*, "Droplet Hi-C enables scalable, single-cell profiling of chromatin architecture in heterogeneous tissues," *Nat Biotechnol*, Oct. 2024, doi: 10.1038/s41587-024-02447-1.

[11] A. Sasse, M. Chikina, and S. Mostafavi, "Unlocking gene regulation with sequence-to-function models," *Nat Methods*, vol. 21, no. 8, pp. 1374–1377, Aug. 2024, doi: 10.1038/s41592-024-02331-5.

[12] K. E. Wu, K. E. Yost, H. Y. Chang, and J. Zou, "BABEL enables cross-modality translation between multiomic profiles at single-cell resolution," *Proc Natl Acad Sci U S A*, vol. 118, no. 15, p. e2023070118, Apr. 2021, doi: 10.1073/pnas.2023070118.

[13] T. Ashuach, M. I. Gabitto, R. V. Koodli, G.-A. Saldi, M. I. Jordan, and N. Yosef, "MultiVI: deep generative model for the integration of multimodal data," *Nat Methods*, vol. 20, no. 8, pp. 1222–1231, Aug. 2023, doi: 10.1038/s41592-023-01909-9.

[14] L. Alzubaidi *et al.*, "Review of deep learning: concepts, CNN architectures, challenges, applications, future directions," *J Big Data*, vol. 8, no. 1, p. 53, Mar. 2021, doi: 10.1186/s40537-021-00444-8.

[15] A. Vaswani *et al.*, "Attention is All you Need".

[16] K. Sokolova, K. M. Chen, Y. Hao, J. Zhou, and O. G. Troyanskaya, "Deep Learning Sequence Models for Transcriptional Regulation," *Annual Review of Genomics and Human Genetics*, vol. 25, no. 1, pp. 105–122, Aug. 2024, doi: 10.1146/annurev-genom-021623-024727.

[17] M. Chiliński and D. Plewczynski, "HiCDiffusion - diffusion-enhanced, transformer-based prediction of chromatin interactions from DNA sequences," *BMC Genomics*, vol. 25, no. 1, p. 964, Oct. 2024, doi: 10.1186/s12864-024-10885-z.

[18] R. Yang *et al.*, "Epiphany: predicting Hi-C contact maps from 1D epigenomic signals," *Genome Biol*, vol. 24, no. 1, p. 134, Jun. 2023, doi: 10.1186/s13059-023-02934-9.

[19] V. R. Gao *et al.*, "ChromaFold predicts the 3D contact map from single-cell chromatin accessibility".

[20] R. Wang, W. Ma, A. S. Mohammadi, S. Shahsavari, S. Vosoughi, and X. Wang, “Improving Cell-type-specific 3D Genome Architectures Prediction Leveraging Graph Neural Networks,” May 21, 2024. doi: 10.1101/2024.05.21.595047.

[21] J. Tan *et al.*, “Cell-type-specific prediction of 3D chromatin organization enables high-throughput in silico genetic screening,” *Nat Biotechnol*, vol. 41, no. 8, pp. 1140–1150, Aug. 2023, doi: 10.1038/s41587-022-01612-8.

[22] G. Fudenberg, D. R. Kelley, and K. S. Pollard, “Predicting 3D genome folding from DNA sequence with Akita,” *Nat Methods*, vol. 17, no. 11, pp. 1111–1117, Nov. 2020, doi: 10.1038/s41592-020-0958-x.

[23] A. V. Luzhin *et al.*, “LASCA: loop and significant contact annotation pipeline,” *Sci Rep*, vol. 11, no. 1, p. 6361, Mar. 2021, doi: 10.1038/s41598-021-85970-4.

[24] S. S. P. Rao *et al.*, “A 3D Map of the Human Genome at Kilobase Resolution Reveals Principles of Chromatin Looping,” *Cell*, vol. 159, no. 7, pp. 1665–1680, Dec. 2014, doi: 10.1016/j.cell.2014.11.021.

[25] M. J. Rowley *et al.*, “Analysis of Hi-C data using SIP effectively identifies loops in organisms from *C. elegans* to mammals,” *Genome Res.*, vol. 30, no. 3, pp. 447–458, Mar. 2020, doi: 10.1101/gr.257832.119.

[26] A. Roayaei Ardakany, H. T. Gezer, S. Lonardi, and F. Ay, “Mustache: multi-scale detection of chromatin loops from Hi-C and Micro-C maps using scale-space representation,” *Genome Biol*, vol. 21, no. 1, p. 256, Dec. 2020, doi: 10.1186/s13059-020-02167-0.

[27] C. Hou, R. Dale, and A. Dean, “Cell type specificity of chromatin organization mediated by CTCF and cohesin,” *Proc Natl Acad Sci U S A*, vol. 107, no. 8, pp. 3651–3656, Feb. 2010, doi: 10.1073/pnas.0912087107.

[28] Y. Liu and J. Dekker, “CTCF-CTCF loops and intra-TAD interactions show differential dependence on cohesin ring integrity,” *Nat Cell Biol*, vol. 24, no. 10, pp. 1516–1527, Oct. 2022, doi: 10.1038/s41556-022-00992-y.

[29] H. M. A. M. Chowdhury, T. Boult, and O. Oluwadare, “Comparative study on chromatin loop callers using Hi-C data reveals their effectiveness,” *BMC Bioinformatics*, vol. 25, no. 1, p. 123, Mar. 2024, doi: 10.1186/s12859-024-05713-w.

[30] A. Del Moral-Morales, M. Salgado-Albarrán, Y. Sánchez-Pérez, N. K. Wenke, J. Baumbach, and E. Soto-Reyes, “CTCF and Its Multi-Partner Network for Chromatin Regulation,” *Cells*, vol. 12, no. 10, p. 1357, May 2023, doi: 10.3390/cells12101357.

[31] T. Yang *et al.*, “HiCRep: assessing the reproducibility of Hi-C data using a stratum-adjusted correlation coefficient,” *Genome Res.*, vol. 27, no. 11, pp. 1939–1949, Nov. 2017, doi: 10.1101/gr.220640.117.

[32] S. Rajderkar *et al.*, “Topologically associating domain boundaries are required for normal genome function,” *Commun Biol*, vol. 6, no. 1, p. 435, Apr. 2023, doi: 10.1038/s42003-023-04819-w.

[33] W. Makałowski, “The human genome structure and organization.,” *Acta Biochim Pol*, vol. 48, no. 3, pp. 587–598, Sep. 2001, doi: 10.18388/abp.2001_3893.

[34] S. Wang *et al.*, “HiNT: a computational method for detecting copy number variations and translocations from Hi-C data,” *Genome Biol*, vol. 21, no. 1, p. 73, Dec. 2020, doi: 10.1186/s13059-020-01986-5.

[35] T. Gao and J. Qian, “EnhancerAtlas 2.0: an updated resource with enhancer annotation in 586 tissue/cell types across nine species,” *Nucleic Acids Research*, p. gkz980, Nov. 2019, doi: 10.1093/nar/gkz980.

[36] S. Müller-Dott *et al.*, “Expanding the coverage of regulons from high-confidence prior knowledge for accurate estimation of transcription factor activities,” *Nucleic Acids Research*, vol. 51, no. 20, pp. 10934–10949, Nov. 2023, doi: 10.1093/nar/gkad841.

[37] Z. Zou, T. Ohta, and S. Oki, “ChIP-Atlas 3.0: a data-mining suite to explore chromosome architecture together with large-scale regulome data,” *Nucleic Acids Research*, vol. 52, no. W1, pp. W45–W53, Jul. 2024, doi: 10.1093/nar/gkae358.

[38] C. Feng *et al.*, “KnockTF 2.0: a comprehensive gene expression profile database with knockdown/knockout of transcription (co-)factors in multiple species,” *Nucleic Acids Research*, vol. 52, no. D1, pp. D183–D193, Jan. 2024, doi: 10.1093/nar/gkad1016.