Benchmarking Alignment Strategies for Hi-C Reads in Metagenomic Hi-C Data

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Abstract

Background: Metagenomics combined with High-throughput Chromosome Conformation Capture (Hi-C) offers a powerful approach to study microbial communities by linking genomic content with spatial interactions. Hi-C enhances shotgun sequencing by revealing taxonomic composition, functional interactions, and genomic organization from a single sample. However, aligning Hi-C reads to metagenomic contigs presents challenges, including the unique statistical distribution of Hi-C paired-end reads, multi-species complexity, and gaps in assemblies. Although many benchmark studies have evaluated general alignment tools and Hi-C data alignment, none have specifically addressed metagenomics Hi-C data.
Results: Here, we selected seven alignment strategies that have been used in Hi-C analyses: BWA MEM -5SP, BWA MEM default, BWA aln default, Bowtie2 default, Bowtie2 –very-sensitive-local, Minimap2 default, and Chromap default. We benchmarked them on one synthetic and seven real-world environments, and evaluated these tools based on the number of inter-contig Hi-C read pairs and their influence on downstream tasks, such as binning quality.
Conclusion: Our findings show that BWA MEM -5SP consistently outperforms other tools across all environments in terms of inter-contig read pairs and binning quality, followed by BWA MEM default. Chromap and Minimap2, while less effective in these metrics, demonstrate the highest computational efficiency.

Keywords: Hi-C Metagenomics, Sequence Alignment, Benchmarking

1 Introduction

Metagenomics is the study of the collective genomes of all microorganisms present in a given microecosystem, offering insights into the composition, diversity, and functions of microbial communities. A more recent technique, High-throughput Chromosome Conformation Capture (Hi-C), enables the study of long-range DNA interactions across the genome in an unbiased, genome-wide manner and can be effectively combined with metagenomics [1]. When integrated with metagenomics, Hi-C enhances traditional shotgun sequencing by providing spatial context to microbial genomes, enabling a deeper understanding of microbial communities. This combined approach not only elucidates the taxonomic composition of a sample but also reveals the interactions of microbial genomes.

The pipeline for generating metagenomic Hi-C (metaHi-C) data has become increasingly more streamlined and standardized. The process begins with collecting environmental samples from the same microbial community, producing shotgun reads via high-throughput sequencing such as Illumina or PacBio and Hi-C reads through paired-end Illumina sequencing. Long-read metaHi-C datasets typically refer to those generated from long-read shotgun libraries using PacBio or Nanopore sequencing, whereas short-read metaHi-C datasets are derived from short-read shotgun libraries using Illumina sequencing. In Hi-C experiments, DNA is crosslinked to preserve spatial interactions within intact microbial cells, and proximity ligation is performed to create chimeric DNA molecules that link physically adjacent genomic regions [2]. These ligation products are then fragmented, sequenced, and used to infer genomic organization and interactions between different regions. Next, the shotgun reads are assembled into contigs. Hi-C reads are then aligned to these contigs to produce a raw metagenomic Hi-C contact matrix where rows and columns correspond to genomic regions or contigs. Each entry in the matrix represents interaction frequency, reflecting their spatial proximity. This contact matrix can be normalized to correct for biases and is subsequently used for genomic binning or other downstream analyses.

A critical step in the metagenomic Hi-C analysis pipeline is the alignment of Hi-C reads to assembled contigs, as it directly impacts the quality of the raw contact matrix. However, aligning Hi-C reads to metagenomic contigs poses unique challenges. First, Hi-C data contains paired reads originating from distant regions, which follow a statistical distribution that differs significantly from that of shotgun libraries. Second, metagenomic datasets include genomes from multiple species, adding complexity to the alignment process. Third, gaps between assembled contigs can lead to lower mapping rates. As a result, general-purpose alignment tools require adjustments to effectively align Hi-C reads to assembled contigs. While there are some benchmark studies evaluating general alignment tools [3, 4], no comprehensive benchmarks exist for metagenomic Hi-C data specifically. Moreover, there is no consensus on a standardized alignment strategy in Hi-C analyses, and various tools have been employed

across different studies. For example, Stalder et al [5] used BWA MEM [6], Baudry et al [7] used Bowtie2 [8], Wang et al [9] applied Chromap [10], and Gounot el al [11] leveraged Minimap2 [12]. This variability highlights the need for a systematic benchmark specifically designed to address the unique requirements of alignment tools for metaHi-C data.

2 Overview of Alignment Methods for Hi-C data

Alignment methods for metagenomics Hi-C data are essential for processing and analyzing the interactions between metagenomic fragments. These alignment methods aim to map sequencing reads from Hi-C libraries to assembled contigs, facilitating the identification of intra- and inter-contig interactions. In the following, we will briefly review some of the alignment programs that have been used in Hi-C data analysis.

BWA is one of the most widely used alignment tools in genomics due to its efficiency and adaptability to various sequencing data types. It uses the Burrows-Wheeler Transform (BWT) and FM-index to compress the reference genome, enabling fast and memory-efficient alignments [6]. Bowtie2 is another popular aligner for Hi-C data, known for its speed and flexibility. Like BWA, it leverages the BWT and FM-index for efficient alignment yet introduces enhancements for gapped alignments and supports dynamic programming to facilitate local alignment [8]. Chromap and Minimap2 are two other tools employed for Hi-C alignment. Chromap is a recently developed alignment tool [10], designed specifically for chromatin-focused experiments such as Hi-C [13], ChIP-seq [14], and ATAC-seq [15]. It uses a minimizer sketch and split-alignment for efficient and specialized read alignment [10]. Minimap2, originally developed for aligning genomic DNA only, has been extended to map mRNAs as well, making it one of the first RNA-seq aligners specifically designed for long noisy reads [12].

2.1 Challenges of Aligning MetaHi-C Reads to Assembled Contigs

Aligning Hi-C reads to metagenomically assembled contigs presents several unique challenges due to the nature of Hi-C data and the complexities of metagenomic assemblies. First, Hi-C data intentionally contains paired reads which can come from very far away genomic regions. Most aligners in paired-end mode operate under the assumption that the paired reads are derived from a single continuous genomic fragment, with an insert size that fits within a known distribution [16]. However, Hi-C ligation products can vary dramatically in size, ranging from 1 bp to hundreds of megabases in terms of linear genomic distance [16]. This makes it challenging to directly apply standard paired-end alignment modes to Hi-C data, as the statistical distribution of paired reads is fundamentally different [17]. Consequently, only a few alignment tools, such as Minimap2, BWA, and Chromap, natively support chimeric alignments and are suitable for Hi-C data.

Secondly, a microbial community often contains hundreds or thousands of microbial organisms, with genome abundance levels varying widely [18]. Additionally, some microbial genomes are highly similar, which can result in ambiguous mapping of Hi-C reads. This similarity, combined with the inherent variability in genome abundance,

complicates alignment further, as Hi-C reads can be ambiguously mapped, potentially resulting in low mapping quality of inter-contig relationships.

Lastly, metagenomic assemblies often have gaps between contigs that may not fully represent the complete genomes of all present species, especially in regions with repetitive sequences [19]. When Hi-C reads are aligned to metagenomic assembled contigs, regions near assembly gaps may experience lower alignment accuracy or complete lack of alignment due to missing sequences. These challenges underline the need for alignment tools or robust strategies to effectively map Hi-C reads to metagenomic assemblies.

2.2 Selected Alignment Strategies

To evaluate the performance of different alignment methods on metagenomic Hi-C data, we selected seven widely used alignment strategies and tested them on eight environments. The first three strategies—BWA MEM (P) with the -5SP parameter, BWA MEM (P) with default settings, and BWA aln (S) with default settings—are part of the BWA software package, which employs the Burrows-Wheeler Transform (BWT) for string matching. Here, (P) and (S) refer to paired-read and single-read alignment mode, respectively. BWA aln is tailored for short-read alignment. Burton et al [20] used -n 0 on the synthetic yeast metaHi-C dataset, enforcing global alignment with zero mismatches. While effective for the synthetic dataset, we found that the parameter -n 0 is too stringent for real metaHi-C datasets, resulting in notable low mapping rate (Supplementary Table 1). Therefore, in this paper, we opted to use BWA aln with default parameters instead. Compared to BWA aln, BWA MEM is optimized for longer sequences, ranging from 70 base pairs to several megabases. Using the "-5SP" parameter in BWA MEM, read pairing and mate-pair rescue functions were deactivated and primary alignments forced to be the alignment with lowest read coordinate (5' end) [21].

The next two strategies, Bowtie2 (S) with default settings and Bowtie2 (S) with the –very-sensitive-local parameter, originate from the Bowtie2 aligner. Bowtie2 excels at aligning reads ranging from approximately 50 bases to one thousand bases, particularly well-suited for aligning to long genomes [8]. The –very-sensitive-local setting adjusts multiple parameters to maximize sensitivity for local alignment.

The final two strategies, Minimap2 and Chromap, were tested using their default parameters. Minimap2 is a versatile sequence alignment tool capable of aligning DNA or mRNA sequences to large reference databases. Chromap is specifically designed for ultrafast alignment and preprocessing of high-throughput chromatin profiles. A detailed description of the parameters, settings, and usage examples in Hi-C studies for each strategy is provided in Table 1.

3 Results

3.1 Benchmarking Results for Long-Read MetaHi-C Datasets

We first evaluated the number of inter-contig Hi-C read pairs identified by different alignment strategies. The corresponding result is shown in Fig. 1. BWA MEM -5SP

Table 1 Summary of the seven alignment strategies evaluated in this study, including their descriptions and usage examples. In the "Methods" column, (P) indicates paired-end alignment mode, while (S) represents single-end alignment mode.

Methods	Parameter	Description	Usage Example
BWA MEM (P)	default	BWA maps DNA sequences against a large reference genome. BWA MEM supports long reads and chimeric alignment.	Stalder et al[5], Ivanova et al[22]
BWA MEM (P)	-5SP	"-5" forces the alignment to start with 5' end. "SP" skips mate rescue and pairing.	Beyi et al[23], Hwang et al[24], Bickhart et al[25]
BWA aln (S)	default	Specifically designed for aligning short DNA sequencing reads (typically up to 100 bp) to a reference genome.	Burton et al[20]
Bowtie2 (S)	default	Bowtie 2 is an ultrafast and memory-efficient tool for aligning sequencing reads to long reference sequences.	Kalmart et al[26]
Bowtie2 (S)	–very-sensitive-local	Performing local alignment and maximizing alignment sensitivity.	Baudry et al[7], Marbouty et al[27]
Minimap2 (P)	default	Minimap2 is a versatile sequence alignment program that aligns DNA or mRNA sequences against a large reference database.	Gounot et al[11]
Chromp (P)	default	Chromap is an ultrafast method for aligning and preprocessing high throughput chromatin profiles.	Wang et al[9]

significantly outperformed other strategies for both long reads datasets (sheep gut and cow rumen), highlighting its superior ability to detect interactions between different genomic regions. In the sheep gut dataset (Fig. 1A), BWA MEM -5SP captures 999,896 inter-contig Hi-C read pairs. Minimap2 and BWA MEM default rank second and third, capturing 757,817 and 677,105 Hi-C read pairs, respectively. In contrast, Chromap had the poorest performance, identifying only 170,415 Hi-C read pairs. In the cow rumen dataset (Fig. 1B), BWA MEM -5SP captures 665,999 inter-contig Hi-C read pairs. BWA MEM default and Chromap follow, detecting 587,641 and 518,855 read pairs. Minimap2 demonstrated the lowest performance, identifying only 229,096 Hi-C read pairs.

From the alignment BAM files, we observed that the mapping rate, defined as the percentage of Hi-C reads successfully aligned to metagenomically assembled contigs, was significantly lower for the cow rumen dataset compared to the sheep gut dataset.

For instance, using BWA MEM -5SP, the cow rumen dataset achieved a mapping rate of 51.55%, compared to 85.53% for the sheep gut dataset. This discrepancy arises from differences in the shotgun libraries: the cow rumen dataset was derived from error-prone PacBio long reads, whereas the sheep gut dataset was based on highly accurate HiFi reads. As a result, mapping accurate Hi-C reads to an error-prone long-read assembly leads to a lower mapping rate.

As for the binning results based on CheckM2, BWA MEM -5SP achieved the highest total number of bins with contamination below 5% and completeness $\geq$ 50%. Moreover, in the sheep gut dataset (Fig. 1C), it identified the most bins meeting the stringent threshold of $\geq$ 90% completeness and contamination below 5%. BWA MEM default also showed good performance similar to BWA MEM -5SP, ranked second. In contrast, Chromap demonstrated the weakest performance, yielding the lowest binning results across all metrics. A similar trend was observed when the contamination is below 10% (Fig. 1D). In the cow rumen dataset (Fig. 1E), BWA MEM -5SP and Chromap default produced the second-highest number of bins with contamination below 5% and completeness $\geq$ 50%, while BWA MEM default demonstrated the best performance. Under more relaxed criteria (Fig. 1F), BWA MEM -5SP outperformed all aligners, generating the most bins with contamination below 10% and completeness $\geq$ 50%, followed by BWA MEM default and Chromap default.

In long-read metaHi-C datasets, BWA MEM -5SP consistently outperforms other alignment strategies in detecting inter-contig Hi-C read pairs and achieving superior binning quality. In contrast, the performance of other strategies varies depending on the environmental context.

3.2 Benchmarking Results for Short-Read MetaHi-C Datasets

3.2.1 Synthetic Yeast Dataset

We compared the number of inter-contig Hi-C read pairs identified by each alignment strategies shown in Fig. 2A. Among the tested strategies, the BWA-based approaches outperformed Bowtie2, Minimap2, and Chromap in detecting inter-contig read pairs. Notably, BWA MEM with the -5SP parameter identified the highest number of inter-contig Hi-C read pairs. BWA MEM with default parameters and BWA aln ranked second and third, respectively.

Leveraging the known species identities of all contigs in this synthetic dataset, we further evaluated clustering performance using the Fowlkes-Mallows score (F-score), Adjusted Rand Index (ARI), and Normalized Mutual Information (NMI) as shown in Fig. 2B. While all seven alignment strategies exhibited robust performance, BWA MEM -5SP achieved the highest scores across all three metrics, followed by Minimap2 and BWA MEM with default settings.These results indicate that the clusters produced by BWA MEM -5SP align most accurately with the true species-level clustering of contigs. Overall, based on the number of inter-contig read pairs identified and clustering performance, BWA MEM -5SP demonstrates the best performance among all the alignment strategies tested in this synthetic yeast dataset.

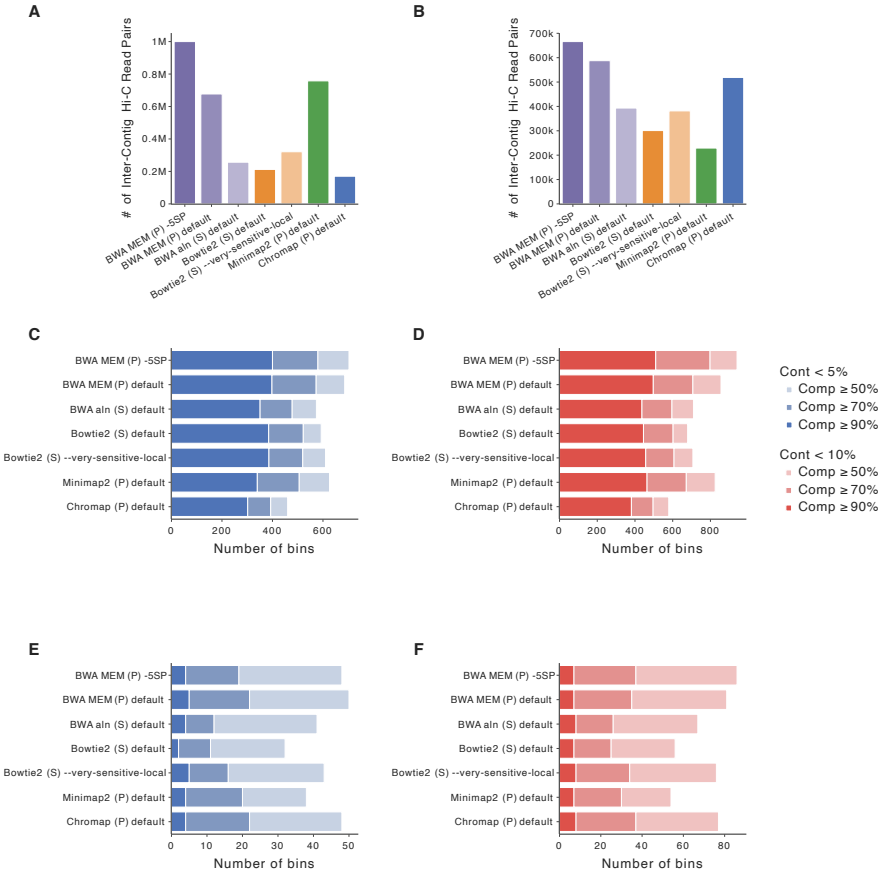

Fig. 1 The long-read metagenomics Hi-C datasets benchmarking results. In the legend, "Cont" stands for Contamination, and "Comp" stands for Completeness. **A**: The number of inter-contig read pairs captured using different alignment strategies in the sheep gut dataset. **B**: The number of inter-contig read pairs captured using different alignment strategies in the cow rumen dataset. **C**: The number of bins with contamination $< 5\%$ and completeness $\geq 50\%$, 70%, and 90% in the sheep gut dataset. **D**: The number of bins with contamination $< 10\%$ and completeness $\geq 50\%$, 70%, and 90% in the sheep gut dataset. **E**: The number of bins with contamination $< 5\%$ and completeness $\geq 50\%$, 70%, and 90% in the cow rumen dataset. **F**: The number of bins with contamination $< 10\%$ and completeness $\geq 50\%$, 70%, and 90% in the cow rumen dataset.

3.2.2 Real Short-Read MetaHi-C Datasets

Using evaluation metrics similar to those applied to long-read metaHi-C datasets, we first compare the number of inter-contig Hi-C read pairs captured by different alignment strategies. For single-dataset environments, such as bovine and wastewater, BWA MEM -5SP consistently detects the highest number of inter-contig read pairs. Similarly, for multi-dataset environments, including hydrothermal mats, pigs, and human gut environments, BWA MEM -5SP achieves the best performance in most datasets, demonstrating its effectiveness across a diverse range of metagenomic Hi-C datasets.

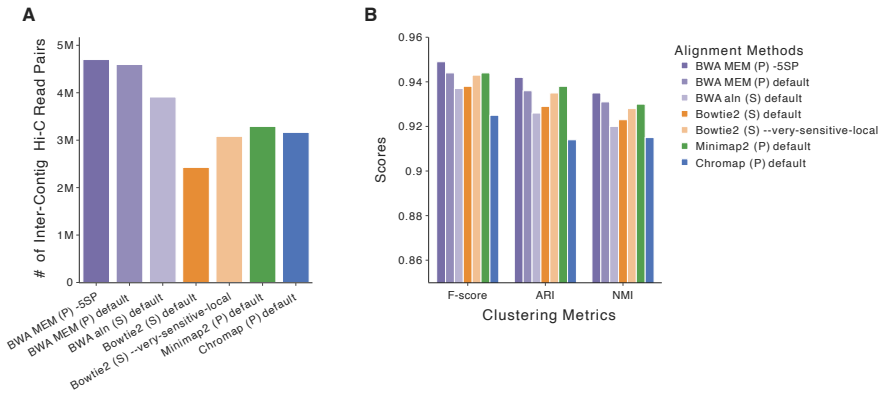

Fig. 2 The synthetic yeast dataset benchmarking results. A: The number of inter-contig read pairs captured and **B**: the clustering performance metrics (F-score, ARI, and NMI) for different alignment strategies.

For the bovine dataset in Fig. 3A, BWA MEM -5SP captured the highest number of inter-contig Hi-C read pairs, totaling 3,514,606. BWA MEM default ranked second with 2,700,382 inter-contig read pairs. In contrast, Bowtie2 and Chromap performed similarly, capturing approximately one-fifth of the read pairs detected by BWA MEM -5SP. For the wastewater dataset in Fig. 3B, BWA MEM -5SP identified 20,529,313 inter-contig Hi-C read pairs. BWA MEM default again ranked second with 13,032,526 read pairs, followed by Minimap2, which detected 11,857,420 read pairs. In contrast, strategies such as Bowtie2 (default and very-sensitive-local modes) detected fewer than 5,000,000 inter-contig read pairs, yielding the lowest count among all strategies. For the human gut environment in Fig. 3C, BWA-MEM -5SP demonstrated consistent superiority, detecting the highest number of inter-contig Hi-C read pairs in 23 out of 24 datasets. BWA MEM default ranked second, identifying a substantial number of inter-contig Hi-C read pairs across most datasets, though consistently performing below BWA MEM -5SP. Its performance showed a strong correlation with that of BWA MEM -5SP; when the performance of BWA MEM -5SP declined, BWA MEM default also exhibited a significant drop. Among the other strategies, Minimap2 exhibited moderate performance, while Chromap consistently detected the lowest number of inter-contig Hi-C read pairs. A similar trend was observed in the hydrothermal mats and pigs environments (Supplementary Figures 1 and 2), where BWA-MEM -5SP consistently detected the highest number of inter-contig Hi-C read pairs, followed by BWA-MEM with default settings.

BWA MEM -5SP excels not only in identifying inter-contig Hi-C read pairs but also in producing the best binning results among all alignment strategies. For the bovine dataset (Fig. 4A), BWA MEM -5SP achieved the highest total number of bins with contamination below 5% and completeness $\geq$ 50%, followed by BWA MEM default. Conversely, Chromap identified the fewest bins meeting these criteria. A similar trend was observed when the contamination threshold was set to below 10% (Fig. 4B). For the wastewater dataset (Fig. 4C), BWA-MEM -5SP generated nearly twice as many

bins with contamination $< 5\%$ and completeness $\geq 50\%$ compared to BWA aln. It ranked first overall, generating the most bins with contamination $< 5\%$ and completeness $\geq 90\%$. Minimap2 and BWA-MEM default ranked second and third, producing 62 and 60 nearly complete bins, respectively. The trend is similar when contamination $< 10\%$ (Fig. 4D). For the hydrothermal mats environment (Fig. 5A), BWA MEM -5SP achieved the best binning results in 6 out of 10 datasets, generating the highest number of bins with contamination $< 5\%$ and completeness $\geq 90\%$. Even in the three datasets where it was not the top-performing aligner, BWA MEM -5SP still ranked highly, outperforming most other strategies. BWA MEM -5SP demonstrated the best performance in bins with contamination $< 10\%$ and completeness $\geq 90\%$ across 9 out of 10 datasets when using a more lenient contamination threshold (Fig. 5B). In the pigs environment (Fig. 5C), BWA MEM -5SP maintained its top performance, producing the highest number of bins with contamination $< 5\%$ and completeness $\geq 90\%$ in 17 out of 20 datasets. Notably, it generated over 65 bins meeting these criteria for dataset CV2_1 and delivered strong results in other datasets such as CV7_2 and CV10_1. BWA MEM default also performed well, ranking second in overall binning quality. While it produced substantial numbers of bins with contamination $< 5\%$ and completeness $\geq 90\%$ across most datasets, it consistently lagged behind BWA-MEM -5SP. When contamination is less than 10%, a silimar trend was observed in (Fig. 5D), followed by BWA MEM default and Minimap2 default. For the human gut environment (Fig. 5E), BWA MEM -5SP consistently outperformed other strategies in 11 datasets, producing the highest number of bins with contamination $< 5\%$ and completeness $\geq 90\%$. BWA MEM default closely trails BWA MEM -5SP in several datasets such as SPMP03, SPMP19 and SPMP40. Minimap2 also showed strong performance; it performs equally or better than BWA MEM -5SP in 10 datasets. In instances where BWA MEM -5SP did not achieve the best results under the stricter contamination $< 5\%$ and completeness $\geq 90\%$ threshold, it excelled under a more lenient criterion (Fig. 5F). For example, in datasets SPMP21 and SPMP60, it generated 23 and 28 bins with completeness $\geq 90\%$, respectively, achieving performance equal to or better than other alignment strategies.

3.3 Computational Time Complexity

All the datasets were ran on a High-Performance-Cluster (HPC) with a xeon-2640356 16-core CPU node and 100 GB of memory. Fig. 6 presents the execution time of the alignment strategies across different datasets. For the long-read sheep gut dataset (Fig. 6A), Bowtie2 –very-sensitive-local had the highest execution time, while Minimap2 and Chromap exhibited the lowest runtime. Other strategies, including BWA MEM variations, demonstrated intermediate runtimes. In the cow rumen dataset (Fig. 6B), Chromap was the fastest followed by Bowtie2 default and BWA MEM strategies. In short-read yeast dataset (Fig. 6C), Minimap2 had the highest computational efficiency followed by BWA MEM strategies. For the bovine short-read dataset (Fig. 6D), Bowtie2 –very-sensitive-local again displayed the highest runtime, while Chromap achieved the fastest runtime. For the wastewater dataset (Fig. 6E), Minimap2 was the most efficient followed by Chromap and BWA MEM strategies.

For the hydrothermal mats environment with 10 datasets (Fig. 6F), Bowtie2 –very-sensitive-local exhibited greater variability and higher median runtimes compared to BWA MEM strategies and Chromap. In the pigs environment with 20 datasets (Fig. 6G), Minimap2 demonstrated the shortest runtime while Bowtie2 –very-sensitive-local showed longer runtime. Lastly, in the human gut environment with 24 datasets (Fig. 6H), Minimap2 again achieved the most efficient runtime followed by BWA MEM strategies. Overall, Chromap and Minimap2 are the most computationally efficient strategies, though their performance exhibits some variability across different environments. BWA MEM strategies exhibited intermediate to relatively low runtimes, while Bowtie2 –very-sensitive-local tended to be the slowest.

4 Discussion

In this work, we evaluated seven commonly used alignment strategies in metagenomics Hi-C: BWA MEM (P) -5SP, BWA MEM (P) default, BWA aln (S) default, Bowtie2 (S) default, Bowtie2 (S) –very-sensitive-local, Minimap2 (P) default, and Chromap (P) default. These alignment strategies are often used to map Hi-C reads to assembled metagenomic contigs. This is an important step in metagenomic Hi-C analysis as it directly affects the quality of the raw metagenomic Hi-C contact matrix. However, there is currently no consensus on the optimal alignment strategy to use for this task. To address this gap, we benchmarked these alignment strategies using one synthetic dataset and seven real datasets. Our results show that while the performance of the alignment strategies varies, BWA MEM -5SP consistently outperforms all others across different environments. BWA MEM default closely follows, demonstrating strong but slightly lower performance compared to BWA MEM -5SP. A key factor contributing to the superior performance of BWA MEM -5SP may be the -5 flag, which forces the primary alignment to be the one with the lowest read coordinate. This feature is particularly advantageous for Hi-C data, where reads often originate from distant genomic regions and may align to multiple contigs due to the fragmented nature of metagenomic assemblies. This -5 flag enforces consistency by always selecting the alignment with the lowest coordinate as the primary alignment, reducing ambiguity in read assignment. Although Chromap and Minimap2 perform less effectively in the evaluation metrics, they demonstrate the highest computational efficiency across most environments. Similarly, BWA MEM strategies also exhibit relatively high computational efficiency.

Although BWA MEM -5SP demonstrated the best overall performance across the eight environments tested, further studies are needed to validate its effectiveness on additional datasets in diverse contexts. Additionally, this study primarily focused on the number of inter-contig Hi-C read pairs and binning quality as performance metrics. Future work should explore a broader range of evaluation metrics to provide a more comprehensive comparison of alignment strategies.

5 Materials and Methods

5.1 Datasets

To evaluate the alignment performance of different strategies, we chose one synthetic yeast dataset and several real metagenomic Hi-C datasets derived from diverse environments. Among the real datasets, five environments are based on short-read shotgun libraries, while the sheep gut and cow rumen environments originate from long-read shotgun libraries. All of them have short-read Hi-C libraries. An overview of these datasets is provided in **Table 2**, and the data is available in Additional file 2.

For the sheep gut long-read metaHi-C dataset [25], it includes PacBio circular consensus sequencing (CCS), or HiFi, long-read libraries and illumina short-read Hi-C libraries. The dataset resulted in 255 Gbp from CCS long-read libraries and 107 million read pairs from Hi-C libraries. The cow rumen long-read metaHi-C dataset [28] includes PacBio uncorrected long-read libraries and Hi-C libraries. The error-prone PacBio long reads were generated using the PacBio RSII and PacBio Sequel platforms, totaling 52 Gbp. The Hi-C libraries were sequenced on an Illumina HiSeq 2000 at 80 bp, producing 63.4 million Hi-C reads.

The synthetic yeast dataset [20] comprises a mixture of 13 yeast species. The raw shotgun libraries consisted of 85.7 million read pairs at 101 bp, while the raw Hi-C libraries contained 81 million read pairs at 100 bp. The bovine dataset [23] provided a total of 21 Gb of sequence data for the shotgun library and 16.8 Gb of Hi-C data, both sequenced using the Illumina HiSeq platform. For the wastewater dataset [5], both Hi-C and shotgun metagenomic libraries were pooled and sequenced using two lanes of the Illumina HiSeq 4000 platform. The shotgun metagenomic library yielded 269,312,499 read pairs, while the Hi-C library produced 95,284,717 read pairs. While the environments discussed above each contain a single dataset, the next three environments include multiple datasets within each. In the hydrothermal mats environment [24], which includes 10 different metaHi-C datasets, both Hi-C and shotgun libraries in each dataset were sequenced on a single lane of an Illumina NovaSeq S4 system, yielding a total of 1.8 billion shotgun read pairs and 1.5 billion Hi-C read pairs, respectively. The sizes of the Hi-C libraries range from 29.1 Gbp to 70 Gbp. For the pigs environment [26], which comprises 20 datasets, both Hi-C and shotgun libraries were sequenced on the Illumina HiSeq 4000 platform. The shotgun libraries generated a total of 3.5 billion reads, while the Hi-C libraries produced 3.1 billion reads with sizes ranging from 7.1 Gbp to 26.9 Gbp. Lastly, the human gut environment [11], consisting of 24 datasets, was generated using paired-end sequencing on the Illumina HiSeq 4000 platform for both metagenomic and Hi-C libraries. The metagenomic library produced a total of 256 Gbp, while the Hi-C library yielded 564 Gbp. Hi-C library sizes range from 2.4 Gbp to 87 Gbp, whereas shotgun library sizes range from 6 Gbp to 23 Gbp. The restriction enzymes used for constructing Hi-C libraries in each environment are listed in Table 2, while a summary of dataset sizes is provided in Additional file 3.

Table 2 Descriptions of eight environments used in the experiments. In the "Long Read / Short Read" column, "Long Read" denotes long-read metaHi-C datasets, and "Short Read" represents short-read metaHi-C datasets. The "Restriction Enzymes" column specifies the restriction enzymes used for constructing each corresponding Hi-C library.

Environment	Description	Long read / Short read	Restriction enzymes
Sheep gut	A fecal sample was taken from a young (<1 year old) wether lamb of the Katahdin breed.	Long	Sau3AI and MluCI
Cow Rumen	Rumen contents from one multiparous Holstein cow housed at the University of Wisconsin, Madison, campus were sampled via rumen cannula.	Long	Sau3AI and MluCI
Synthetic yeast	Mixture of yeasts, consisting of 13 yeast species.	Short	NcoI and HindIII
Bovine	Large pooled samples collected from cows with lesions of DD at slaughterhouses.	Short	Sau3AI and MluCI
Wastewater	The wastewater sample was collected in October 2017 at the Moscow WWTP in Idaho (USA).	Short	Sau3AI and MluCI
Hydrothermal mats	Microbial mat samples were collected during a research expedition.	Short	Sau3AI and MluCI
Pigs	Pig fecal samples came from five conventional pig farms and five organic pig farms.	Short	HpyCH4IV
Human gut	Fecal samples were collected from individuals aged 48 to 76 as part of the Singapore Platinum Metagenomes Project (SPMP).	Short	Sau3AI and MluCI

5.2 Data Preprocessing and Assembly

We processed all datasets using a standardized cleaning procedure with BBTools [29]. First, we used BBDuk (v39.06) from BBTools to trim adapters and perform quality filtering through k-mers on paired-end sequencing reads for both Hi-C and WGS data with parameters 'ktrim=r k=23 mink=11 hdist=1 minlen=50 tpe tbo'. Then, we applied additional quality trimming to sequencing reads with parameters 'trimq=10 qtrim=r ftm=5 minlen=50'. To eliminate potential biases and remove low-quality bases from library preparation, we further trimmed the first 10 bases from the 5' end of each Hi-C and WGS sequencing read (ftl=10). Lastly, we utilized Clumpify (v39.06) from BBTools to deduplicate paired-end Hi-C reads with default parameters. For the short reads datasets, the WGS reads were assembled into contigs using Megahit [30] (v1.2.9) with parameters '–min-contig-len 1000 –k-min 21

–k-max 141 –k-step 12 –merge-level 20,0.95'. For the two long reads datasets, we used the contigs provided in the original studies. Specifically, for the sheep gut dataset, Bickhart et al [25] assembled the Pacbio long reads using metaFlye (v2.7 '—meta —pacbio-hifi') and deposited at https://doi.org/10.5281/zenodo.5228989 under the file '`flye.v29.sheep_gut.hifi.250g.fasta.gz`'. For the cow rumen dataset, PacBio raw reads were assembled by Bickhart et al [28] using Canu (v1.6+101 changes (r8513) with parameters '-trim-assemble genomeSize=5m oeaMemory=32 redMemory=32 correctedErrorRate=0.035'), followed by two rounds of polishing with Illumina data via Pilon. The final assembly is available at https://figshare.com/articles/usda_pacbio_second_pilon_indelsonly_fa_gz/8323154.

5.3 Alignment

For each dataset, we align paired-end Hi-C reads to assembled contigs using seven different strategies. With Bowtie2 (v2.3.5.1), we employed two approaches: (1) single-read mode with default parameters and (2) single-read mode with the –very-sensitive-local option to enable local alignment using the very sensitive preset. For BWA (v0.7.17-r1188), we used three strategies: (1) the BWA aln algorithm in single-read mode with default parameters, (2) the BWA MEM algorithm in paired-read mode with default parameters, and (3) the BWA MEM algorithm in paired-read mode with the -5SP parameter. In addition to those, we applied two more tools: Minimap2 (v2.26-r1175) in paired-read mode with default parameters and Chromap (v0.2.6-r490) with default settings. Following each alignment strategy, the output alignment files were converted to sorted BAM files using SAMtools [31] (v1.18).

5.4 Downstream Analysis

After alignment, we filtered out unmapped reads to ensure only high-quality reads were used for downstream analysis. NormCC, the normalization module of MetaCC [32] (v1.2.0), was used to eliminate the systematic biases from raw metagenomic Hi-C contacts. For the synthetic yeast dataset, the parameters -e NcoI -e HindIII were applied. For the pigs Hi-C datasets, we used parameters -e HpyCH4IV. For other real Hi-C datasets, we set the parameters -e MluCI -e Sau3AI, corresponding to the restriction enzymes used in constructing the Hi-C sequencing libraries. Leveraging the normalized Hi-C contact matrix generated from NormCC, we further used ImputeCC [33] (v1.0.0) with default parameters to bin the contigs for all real Hi-C datasets.

5.5 Evaluation Criteria

To begin, we assess the performance of alignment strategies by comparing their ability to capture inter-contig contacts. Inter-contig contacts are interactions between sequences located on different contigs. Since metagenomics Hi-C experiments are designed to capture contig-to-contig relationships, the number of inter-contig contacts provides a meaningful metric for alignment capability.

Besides counting the number of inter-contig contacts, we further investigate the impact of alignment on downstream analyses, such as binning. We use CheckM2 [34] (v1.0.2) to report bin completeness with contamination thresholds below 5% and 10%.

CheckM2 employs a machine learning-based approach that leverages a larger set of features to estimate the completeness of genome bins, providing a detailed assessment of how much of the genome has been recovered. Additionally, it uses a gradient-boosting model to evaluate the level of contamination in genome bins, suggesting that the genome bin may contain DNA from more than one organism [34].

For the synthetic yeast dataset, unlike the real Hi-C datasets, the ground truth for both intra-species Hi-C contacts and spurious inter-species Hi-C contacts was known (Supplementary Note 1). Since ImputeCC relies on single-copy marker genes of prokaryotes [33], we cannot use ImputeCC to optimize the contig binning process for the yeast dataset. Instead, we directly applied the Leiden graph clustering algorithm with default parameters to the normalized Hi-C contact matrix, clustering contigs into draft genomic bins. To evaluate the performance of contig clustering across different alignment strategies, we computed Fowlkes-Mallows score (F-score), Adjusted Rand Index (ARI), and Normalized Mutual Information (NMI). These metrics provided a comprehensive evaluation of clustering accuracy and alignment performance.

The Fowlkes-Mallows score (F-score) is a metric used to evaluate the similarity between two clusterings, often applied in clustering validation tasks. It is defined as the geometric mean of precision and recall. The score is calculated as follows:

$$\mathrm{F-score} = \sqrt{\frac{TP}{TP+FP} \cdot \frac{TP}{TP+FN}}\,, \tag{1}$$

where TP is true positive, FP is false positive, and FN is false negative. The F-score ranges from 0 to 1, where a score closer to 1 indicates higher similarity between the two clusterings, reflecting better clustering performance.

The Rand Index (RI) is a metric used to measure the similarity between two clusterings by considering the consistency of sample pair assignments. It evaluates how well the predicted clustering agrees with the true clustering by comparing pairwise relationships across all samples.

$$\mathrm{RI} = \frac{TP+TN}{TP+FP+FN+TN}\,, \tag{2}$$

where TN is true negative.

The Adjusted Rand Index is a correction of the Rand Index. While the Rand Index evaluates the similarity between two clusterings, it can be biased by the number of clusters or the size of the dataset, leading to inflated scores even for random clusterings. The ARI corrects this by incorporating the Expected Rand Index, which accounts for the similarity expected by chance. It is defined as follows:

$$\mathrm{ARI} = \frac{\mathrm{RI} - \mathbb{E}(\mathrm{RI})}{\max(\mathrm{RI}) - \mathbb{E}(\mathrm{RI})}\,, \tag{3}$$

where $\mathbb{E}(\mathrm{RI})$ is the Expected Rand Index.

The Normalized Mutual Information is another metric to assess the similarity between two different cluster assignments, providing a score that indicates how much information is shared between the two clusterings. A value closer to 1 means the two

clusters are more similar. Let U and V denote the sets of true class labels and predicted cluster labels, respectively. Define the entropy of a label set S as

$$H(S) = -\sum_{i=1}^{|S|} P(i)\log(P(i))\,, \tag{4}$$

where $P(i) = \frac{|S_i|}{N}$ is the probability of an object in class S_i.

The Mutual Information (MI) between U and V is calculated by:

$$\mathrm{MI}(U,V) = \sum_{i=1}^{|U|}\sum_{j=1}^{|V|} P(i,j)\log(\frac{P(i,j)}{P(i)\times P'(j)})\,, \tag{5}$$

where $P(i,j) = \frac{|U_i \cap V_j|}{N}$, $P(i) = \frac{U_i}{N}$, and $P'(j) = \frac{V_j}{N}$.

Therefore, the Normalized Mutual Information is

$$\mathrm{NMI}(U,V) = \frac{2\times \mathrm{MI}(U,V)}{H(U)+H(V)}\,. \tag{6}$$

Declarations

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Author contributions

Y.D. and F.S. conceived the study and designed the research. Y.W. and Y.D. performed the computational analyses and drafted the manuscript. W.Z. and J.H. collected and analyzed the human gut datasets. All authors contributed to revising and finalizing the manuscript.

Declaration of interests

The authors declare no competing interests.

Consent for publication

All authors have approved the manuscript for submission.

Data Availability

The data used in this study can be accessed and downloaded from Additional file 2.

Code Availability

The benchmarking code is publicly available at https://github.com/yuw053/MetaHi-C_Benchmark.git.

Ethics approval and consent to participate

Not applicable.

Supplementary information

Additional file 1

Supplementary notes, figures and tables (PDF 377 KB). Identifying the species of assembled contigs on the synthetic yeast dataset, supplementary table 1-2 and supplementary figures 1-13 supporting the manuscript.

Additional file 2

Overview of Raw Data Across Environments (xlsx 19 KB). Sheet 1 includes data for the pigs environment, while Sheet 2 contains data for the human gut environment. Sheet 3 provides data for the bovine, hydrothermal mats, wastewater, sheep gut, cow rumen, and synthetic yeast environments.

Additional file 3

The size of shotgun and Hi-C libraries from raw metaHi-C datasets (xlsx 11 KB).

Additional file 4

Overview of runtime Across datasets (xlsx 14 KB). This table provides the detailed runtime for each alignment strategy applied to each dataset.

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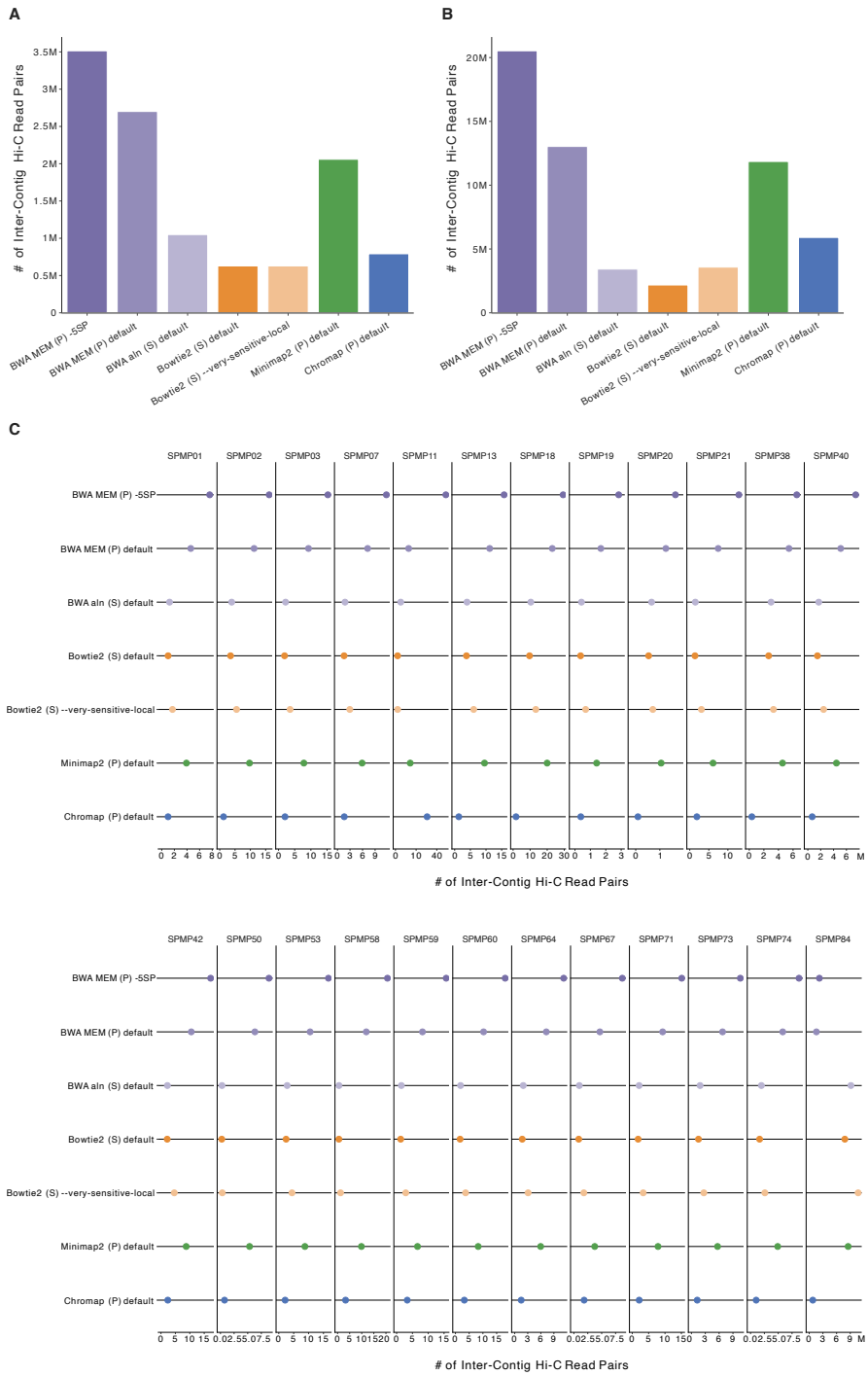

Fig. 3 Comparison of inter-contig read pairs captured by different alignment strategies across various datasets. A: Bovine environment. **B**: Wastewater environment. **C**: Human gut environment.

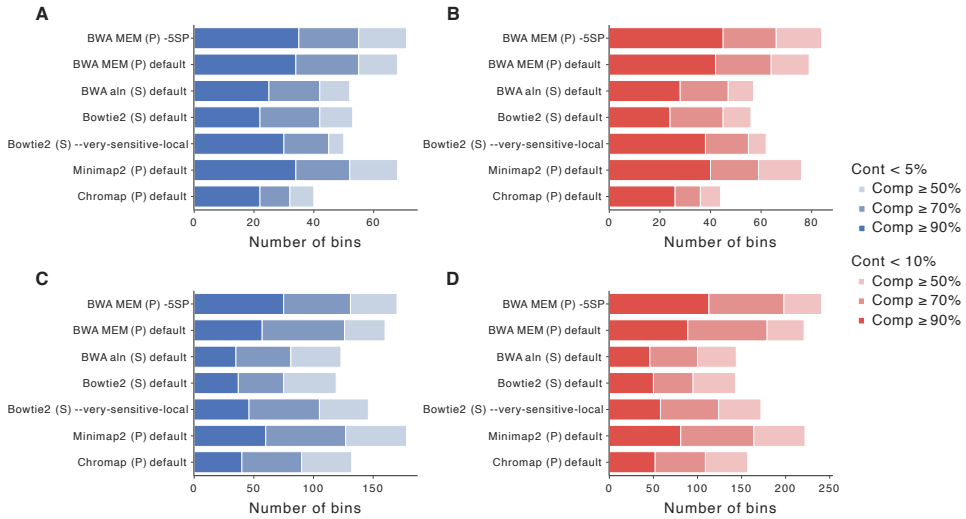

Fig. 4 Comparison of binning results between bovine and wastewater datasets. In the legend, "Cont" stands for Contamination, and "Comp" stands for Completeness. **A**: The number of bins with contamination $< 5\%$ and completeness $\geq 50\%$, 70%, and 90% in the bovine dataset. **B**: The number of bins with contamination $< 10\%$ and completeness $\geq 50\%$, 70%, and 90% in the bovine dataset. **C**: The number of bins with contamination $< 5\%$ and completeness $\geq 90\%$ in the wastewater dataset. **D**: The number of bins with contamination $< 10\%$ and completeness $\geq 90\%$ in the wastewater dataset.

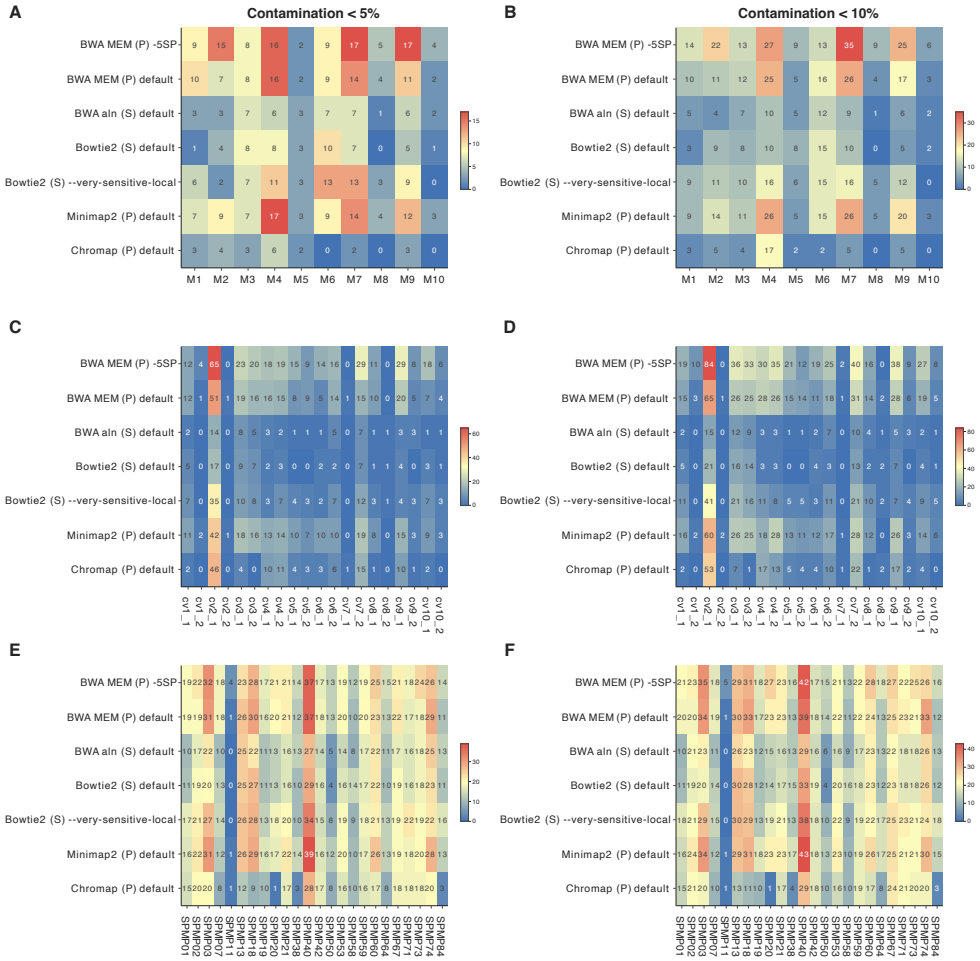

Fig. 5 Comparison of binning results across different alignment strategies and datasets. **A**: The number of bins with contamination $< 5\%$ and completeness $\geq 90\%$ in the hydrothermal mats environment. **B**: The number of bins with contamination $< 10\%$ and completeness $\geq 90\%$ in the hydrothermal mats environment. **C**: The number of bins with contamination $< 5\%$ and completeness $\geq 90\%$ in the pigs environment. **D**: The number of bins with contamination $< 10\%$ and completeness $\geq 90\%$ in the pigs environment. **E**: The number of bins with contamination $< 5\%$ and completeness $\geq 90\%$ in the human gut environment. **F**: The number of bins with contamination $< 10\%$ and completeness $\geq 90\%$ in the human gut environment.

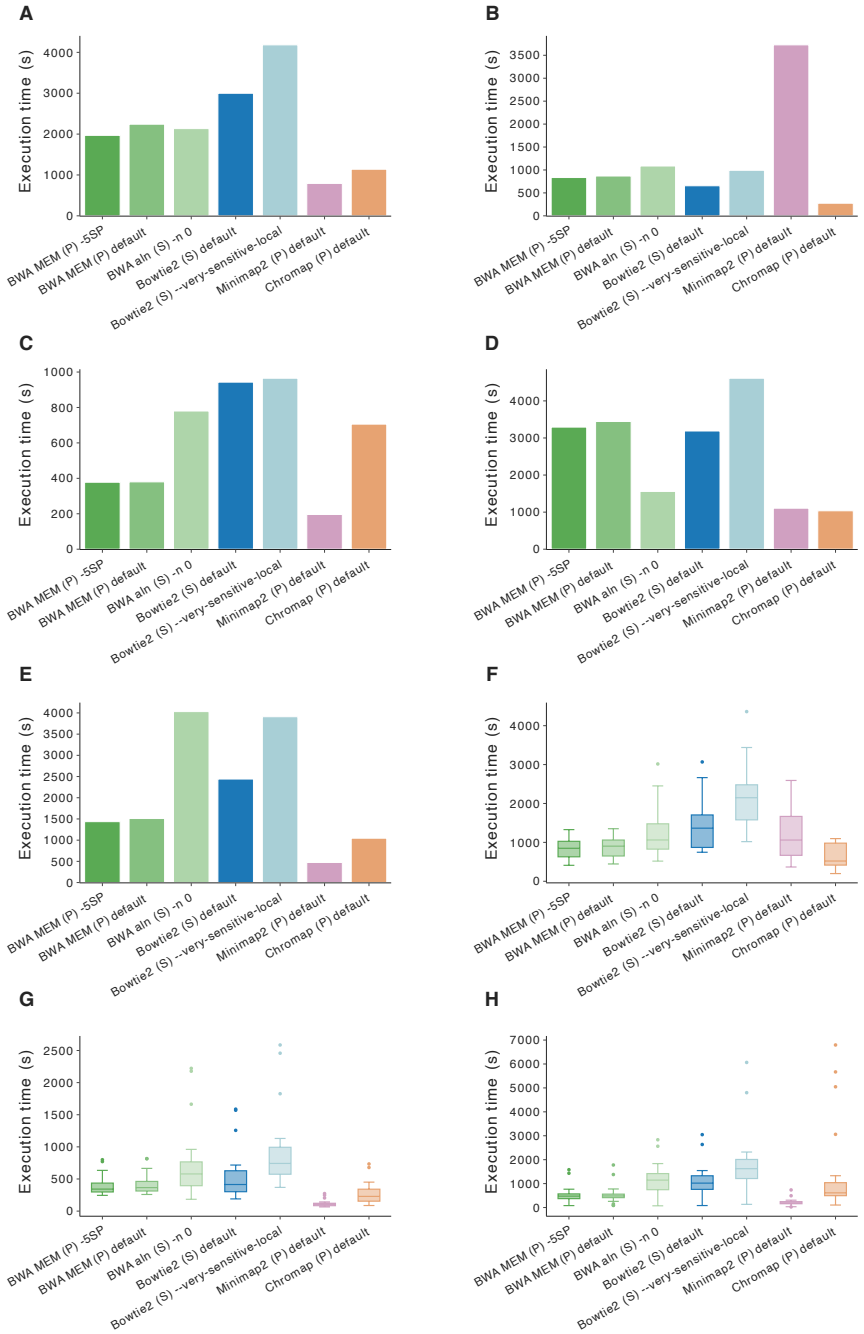

Fig. 6 Runtime comparison of alignment strategies across various datasets. A: Sheep gut environment. **B**: Cow rumen environment. **C**: Synthetic yeast environment **D**: Bovine environment. **E**: Wastewater environment. **F**: Hydrothermal mats environment. **G**: Pigs environment. **H**: Human gut environment.