PathogenSurveillance: an automated pipeline for population genomic analyses and pathogen identification

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Abstract

Whole genome sequencing (WGS) offers a comprehensive, organism-agnostic method that effectively meets the need for efficient, reliable, and standardized responses to emerging threats from pathogens and pests. Here, we present *PathogenSurveillance*, an open-source and automated Nextflow pipeline for population genomic analyses of WGS data. It is designed with features tailored for biosurveillance and is suitable for in-field or point-of-care diagnostics. *PathogenSurveillance* is flexible, accommodating short- and long-read datasets and mixed samples of prokaryotes and/or eukaryotes. It automates all steps, including reference identification and retrieval from the NCBI Assembly database, and produces customizable interactive reports with summaries, phylogenetic trees, and minimum spanning networks that enable species and subspecies level identification. It also outputs quality control metrics and organizes genomic data hierarchically to facilitate downstream analyses. The pipeline runs on any Linux-based system and minimizes the need for advanced computational expertise. Source code is available on GitHub under the open-source MIT license. The pipeline expands the toolkit for real-time biosurveillance, enabling rapid detection and monitoring of pathogens and pests for rapid response to novel variants.

Interpretive summary

PathogenSurveillance is a new open-source tool that helps scientists quickly and reliably detect and monitor harmful organisms like pathogens and pests. It works by analyzing their genetic material, offering a fast and standardized way to respond to emerging biological threats. This tool is designed to be easy to use, even outside of traditional lab settings, such as in the field or at point-of-care locations. It can handle different types of genetic data, including those from bacteria, fungi, and other organisms, and works with both short and long DNA sequences. *PathogenSurveillance* automatically identifies reference genomes from public databases and

generates interactive reports that include summaries, evolutionary trees, and network diagrams. These features help users identify organisms down to the species or subspecies level. It also checks data quality and organizes results to support further analysis. Importantly, it runs on any Linux-based system and doesn't require advanced computing skills. The source code is freely available on GitHub under the MIT license, making it accessible to researchers and public health professionals worldwide. Overall, it adds a powerful tool to the biosurveillance toolkit, enabling faster responses to new and evolving biological threats.

Keywords: bioinformatics, biosurveillance, epidemics, epidemiology, Nextflow, One Health, pipeline, pandemic, pathogen genomics, population genomics

Introduction

Emerging invasive pathogens and pests pose an escalating global threat, largely driven by anthropogenic factors such as intensified international trade (Meyerson and Mooney 2007; Hulme 2009; Fisher et al. 2012; Liebhold et al. 2012). Their sudden appearance and potential to spread rapidly can outpace existing biosurveillance systems, making it difficult to mount timely responses (Carvajal-Yepes et al. 2019). Consequently, diseases caused by these novel organisms may reach epidemic levels before effective diagnostic methods are developed. To address this challenge, biosurveillance efforts require faster and more reliable detection that enables timely interventions (Gardy and Loman 2018; Hamelin et al. 2022). This is especially relevant for OneHealth frameworks, which emphasize the interconnected movement of pathogens across human, animal, and environmental domains, as seen in cases of antimicrobial resistance (Djordjevic et al. 2024).

Whole Genome Sequencing (WGS) is an important tool for biosurveillance, particularly in the early detection of infectious disease outbreaks (Weisberg et al. 2021). Methods for analyzing WGS data are highly effective for detecting emerging or reemerging invasive pathogens and pests, as they do not require *a priori* knowledge or optimization for specific organisms and can be applied to diagnosing rapidly developing threats even when the causative agent is unknown (Gardy and Loman 2018; Weisberg et al. 2021). However, key hurdles to the adoption of WGS are the need for appropriate infrastructure and domain expertise in both computational methods and pathogen biology (Oakeson et al. 2017; Iles et al. 2021). Thus, it is essential to design computational workflows that directly confront these challenges and empower users without specialized training to work with WGS data for disease detection.

WGS-based approaches commonly used for characterizing genetic clustering can be broadly grouped as *k*-mer, multigene, or variant-based phylogenies. *K*-mer based methods have the advantage of being extremely fast and computationally efficient (Pierce et al. 2019). They work by comparing the presence of only exact sequences of a given length (known as *k*-mers). The *k*-mer contents of genome sequences can be summarized by a systematically selected subset of hashed *k*-mers called a sketch and compared to a database of other sketches corresponding to reference genomes (Tian et al. 2020; Irber et al. 2022; Irber et al. 2024). However, sketch-based approaches are limited in their ability to infer taxonomic breadth, as their reliability declines with decreasing genome sequence similarity (Ondov et al. 2016). Conversely, multigene phylogenies can be used to group samples at various taxonomic levels, making such methods

ideal for placing organisms of unknown identities in a phylogenetic context. But these approaches have limited resolution, are less scalable, and require domain knowledge to select appropriate marker gene and reference sequences. The major strength of variant-based (single nucleotide polymorphisms (SNPs)) analyses lies in their high resolution, which enables clustering of closely related samples to identify clonal relationships and reveal potential transmission events. Variant-based approaches have similar limitations as multigene phylogeny-based approaches and are even more sensitive to reference selection and assembly quality (Weisberg et al. 2021).

Various pipelines have been developed for pathogen surveillance. *PathSeq* can be used to identify pathogens from host samples but relies on read alignment, thus requiring a reference database of potential microbes and host sequences (Walker et al. 2018). *Bactopia* and *Galaxy @Sciensano* are collections of seamlessly integrated tools, but they are designed for prokaryotes and require domain knowledge to select appropriate reference sequences (Petit and Read 2020a; Bogaerts et al. 2025). *CZ ID* (formerly *IDseq*) is a web-based pipeline for analyzing metagenomic data for pathogen detection but does not generate multigene phylogenies or high-resolution variant analyses (Kalantar et al. 2020). *Pathogenwatch* is a web service that relies largely on Multi-Locus Sequence Alignment (MLSA) based phylogenetic analyses but has utility for in-depth analyses (Argimón, David, et al. 2021; Argimón, Yeats, et al. 2021; Sánchez-Busó et al. 2021). However, *Pathogenwatch* is not optimized for use on local machines or private clouds and many of its tools are limited to specific pathogen groups. *PathoGFAIR* provides a Galaxy-based workflows to detect and track pathogens from metagenomic Nanopore sequencing (Nasr et al. 2025). Here we present nf-core/*PathogenSurveillance,* an open-source pipeline for automated population genomic and evolutionary analysis. This pipeline was released within nf-core, a collaborative, community-driven framework for developing and sharing standardized pipelines built on the Nextflow workflow management system (Di Tommaso et al. 2017).

PathogenSurveillance leverages nf-core modules and leverages community peer review to ensure robust functionality, while its use of Nextflow provides scalability, reproducibility, and portability. *PathogenSurveillance* automatically processes and analyzes short- and long-read WGS data along with publicly available genome assemblies. It features specialized capabilities for pathogen and pest identification, including flexible support for user-defined or automated reference sequence identification and retrieval, as well as the ability to concurrently analyze mixed prokaryotic and eukaryotic samples and populations. Other distinctive features include the integration of *k*-mer-, multigene phylogeny-, and variant-based approaches to deliver multiple levels of phylogenetic resolution for pathogen identification. The interactive output presents easily interpretable results, facilitating actionable responses. Moreover, output files are organized for deeper downstream investigation, extending use of *PathogenSurveillance* to population genomic studies to a wider range of organisms. To validate and illustrate its utility, we applied *PathogenSurveillance* to test datasets, demonstrating accuracy in automated reference selection and sample identification.

Implementation

We developed *PathogenSurveillance* for WGS data analyses of pathogens or pests. This pipeline is user-friendly and automates all steps from reference sequence selection and retrieval to the

generation of interactive reports detailing sample identity, phylogenetic relationships, and population structure (Figure 1). The pipeline was designed according to widely accepted core principles, with a particular focus on minimizing the need for advanced computational expertise by end users and incorporating specialized features for pathogen surveillance. *PathogenSurveillance* follows the FAIR (Findable, Accessible, Interoperable and Reusable) principles for processing data using workflows (De Visser et al. 2023).

PathogenSurveillance streamlines installation by leveraging Nextflow, an open-source software tool and domain-specific language that simplifies the creation and execution of data-intensive, scientific computational workflows (Di Tommaso et al. 2017). Nextflow uses container frameworks, such as Docker, Apptainer, or Conda, to automatically and reproducibly install all required dependencies as needed and upon first execution. Each process runs in its own isolated container and file system, eliminating software incompatibilities and ensuring consistent behavior across any Linux-based environment. As part of *PathogenSurveillance*'s development, we contributed seven new modules and made updates or bug fixes in eight existing nf-core modules (Supplementary Table 1).

The input process is also streamlined without sacrificing flexibility or configurability. *PathogenSurveillance* minimally requires a tab-separated value (TSV) file as input, with the only mandatory field being source of sequence data. This field can be populated with any combination of paths to local files or URLs to remote files, NCBI Short Read Archive (SRA) accession numbers, or NCBI Biosample IDs associated with SRA accessions. Input data may correspond to a single sample, multiple taxonomically disparate samples — including both prokaryotic and eukaryotic organisms —, populations of related samples, or any combination thereof. While *PathogenSurveillance* also has flexibility in analyzing samples with raw reads derived from Illumina, PacBio, or Oxford Nanopore technologies, it does not support data combined for the same sample from multiple sequencing platforms. For the latter case, users will need to select one source of read data. All other metadata for samples are optional but recommended, if available, to support downstream analyses. Users can also provide a second optional TSV file to specify reference genomes. Furthermore, users can indicate whether user-defined reference genomes should be included or used as the sole source, thereby excluding other possible references from analyses.

The pipeline is initiated with a single command. Upon initiation, it automatically generates a *k*-mer sketch from each sample's raw reads and compares these to sketches of all of NCBI RefSeq using bbmap sendsketch (Figure 1) (Bushnell 2014). If chosen by the user, it then identifies and retrieves assemblies that are possible reference sequences. Next, *PathogenSurveillance* processes and assembles sample reads and generates new *k*-mer sketches using sourmash to infer Average Nucleotide Identity (ANI) values that can be used to refine reference selection (Pierce et al. 2019). The pipeline selects the next workflow branches based on whether the sample is inferred to be of prokaryotic or eukaryotic origin. For prokaryotic datasets, it will annotate genome assemblies, generate ortholog clusters, identify shared orthologs among samples and their references, and construct a core genome phylogenetic tree. If the pipeline identifies clusters of closely related samples, it will map reads to their common reference assembly, call SNPs, and generate a SNP tree as well as a minimum spanning network. For eukaryotic datasets, *PathogenSurveillance* does not annotate genome sequences, as automated annotation is

impractical because taxonomic groups require specialized training datasets. Instead, the pipeline generates a phylogenetic tree based on identified Benchmarking Universal Single-copy Orthologs (BUSCO) sequences (Manni et al. 2021). A final interactive report is generated as an HTML file wherein users can define groups and adjust visualizations. All intermediate files, such as assemblies and annotations, are stored and accessible for additional analyses. *PathogenSurveillance* also produces quality control reports for reads and assemblies. Details on key workflow steps of the pipeline are provided in the following sections. The report created lists all the references or sources for computational tools used in the analysis.

PathogenSurveillance is portable and can be executed on any Linux-based platform, including local desktops, high performance computing (HPC) clusters, and commercial cloud environments. In addition, *PathogenSurveillance* can be launched from Sequera Platform, a web-based platform. A comprehensive guide to executing the pipeline, including input formats and optional parameters, is available online (https://nf-co.re/PathogenSurveillance).

Automated reference selection and population-level analyses

Effective selection of a reference genome and marker gene sequences are critical for accurate pathogen identification (Weisberg et al. 2021). However, the likely taxonomic classification of a sample may not be readily known, particularly for emerging pathogens and pests. To mitigate this limitation, we implemented a rule-based system for context-aware selection and retrieval of reference genome sequences that balances per-sample accuracy with the potential for coherent population-level analyses (Figure 2). By default, *PathogenSurveillance* attempts to automatically detect and group related samples within the analyzed dataset. Users also have the option of manually assigning references to samples or specifying which subgroups of samples should be analyzed together.

As described in the overview, rules are executed in two stages (Figure 1). In the first stage, a subset of possible reference assemblies relevant to the aggregated set of samples are downloaded (Figure 2A). For every unique family identified for samples analyzed, *PathogenSurveillance* will download the corresponding NCBI Assembly metadata, used to further refine reference selection based on genera, species, and strain information. If multiple references are available for a selected taxon, selection is additionally based on the prevalence of the associated taxon in the database indicating it is typical by NCBI standards, whether the assembly corresponds to a type strain, is in RefSeq, and associated with a Latin binomial, as well as assembly features such as assembly level, predicted assembly coverage of the genome sequence, absence of contaminating reads, and contig L50. In the second stage, the pipeline uses estimated ANI values to identify two types of reference assemblies among those downloaded (Figure 2). Contextual references are of well-characterized organisms selected to represent different taxonomic levels for phylogenetic analyses while mapping references are used for SNP calling.

To facilitate population-level analysis, the pipeline identifies contextual references that are shared across samples. This reduces the total number of distinct references and enables grouping of related samples for phylogenetic inference (Figure 2B). References are first partitioned into equal-sized bins based on a rescaled estimated ANI value for each sample. References most similar to each sample and those specified by the user are selected as initial candidates.

PathogenSurveillance then iteratively selects additional references that best serve the entire group of samples. In each iteration, it prioritizes references that span the greatest number of bins across all samples, recalculating bin coverage after each selection. This process continues until every bin is filled by at least one selected reference. This process also helps reduce runtime and computational resources needed to construct the phylogeny.

For prokaryotic samples, core gene sequences are used to construct a phylogeny while for eukaryotic samples, BUSCO gene sequences are used (Manni et al. 2021). If *PathogenSurveillance* determines that too few gene homologs are shared among samples, it partitions the dataset into the fewest possible number of clusters such that each cluster meets the minimum threshold of shared gene homologs required to support robust phylogenetic inference. The default threshold is set to 10 gene homologs.

Mapping reference assembly quality and phylogenetic distance from samples affects the accuracy of SNP calling after read mapping (Iruegas-Bocardo et al. 2023). Moreover, only samples whose reads are aligned to the same mapping reference assembly are directly comparable in population genomic analyses. *PathogenSurveillance* addresses these limitations by using estimated ANI values to cluster samples with their most closely related references in a sequential manner (Figure 2C). The process begins by selecting a reference that exceeds a defined minimum similarity threshold and is shared by the largest number of samples. When multiple references meet estimated ANI thresholds for the same number of samples, the one with the highest average similarity across those samples is chosen. This process is repeated iteratively until no samples can be matched to a reference. For each resulting cluster containing two or more samples assigned to the same reference, a pangenome graph method is executed to call SNPs (Eggertsson et al. 2019). This method is more robust to variation in phylogenetic distance and reference sequence quality (Eggertsson et al. 2019; Weisberg et al. 2021; Iruegas-Bocardo et al. 2023). SNP data is then used to create phylogenetic trees or minimum spanning networks.

***PathogenSurveillance* outputs**

PathogenSurveillance produces a rich set of data that are synthesized in tables and plots in interactive HTML reports for each user-defined group of samples. A sunburst plot provides a summary of taxonomic classifications of the samples, predicted based on initial *k*-mer sketches of raw reads and is associated with a table that presents the statistics for each match. These preliminary classifications, based on analysis of raw reads, serve to guide *PathogenSurveillance* in the next round for selecting reference assemblies. Next, estimated ANI and Percent of Conserved Proteins (POCP) values are displayed as both interactive heatmaps and in a table of best matches for each sample (Qin et al. 2014). These give essential context for interpretation of predicted taxonomic identities, as ANI reflects similarity across homologous regions while POCP captures overall genomic similarity between compared genome sequences (Weisberg et al. 2021). Multilocus, phylogenetic trees provide taxonomic placements of samples (Minh et al. 2020). A minimum spanning network constructed from genetic distances is used to visualize clonal lineages within populations (Kamvar et al. 2014). Table and plots are accompanied by expandable tooltips that explain how to interpret data and outline methods used.

In addition to the main report, *PathogenSurveillance* writes results from each step into structured

folders that can be mined further for downstream analyses (Supplementary Figure 1). These output folders are organized hierarchically and named intuitively. Likewise, output files corresponding to specific samples, references, or groups of samples and references are consistently named based on user-definable identifiers. The organization and naming are intentionally designed to be both human-readable and machine-parseable, facilitating seamless integration into downstream analyses. The kind of analyses used by *PathogenSurveillance* necessarily involve the creation of large and numerous files, not all of which are equally likely to be useful for downstream analysis. Nearly all intermediate files that take up little space are included in the output, but care has been taken to only include large files if their potential utility justifies their storage footprint. For example, quality filtering of BAM and VCF files occurs in several steps, each of which produces large files, but only the raw and final filtered versions of BAM and VCF files are preserved in the output. Additionally, by default all files in the output directory are links to files stored in a cache rather than the files themselves. This is the same cache that is used to resume pipeline runs and skip redundant steps. This has the benefit of only storing a single file when multiple runs of the pipeline produce the same file, as is common when testing multiple variations of a given dataset or pipeline parameters. Together, the careful curation of output files combined with the lack of redundancy significantly reduces the need for disk space, enabling larger analyses and efficient reanalysis of changing datasets.

The outputs also include quality control reports that support the interpretation of results. *PathogenSurveillance* automatically executes several standard quality control programs. FastQC is used to report basic and per read statistics for short read datasets while NanoPlot serves the same purpose for long read datasets (De Coster and Rademakers 2023). The adapter-trimming software, fastp, provides detailed reports on read filtering, trimming, and overall read quality (Chen et al. 2018). Quast is used to assess assembly quality metrics such as contiguity and completeness (Gurevich et al. 2013). BUSCO provides an additional estimate of genome assembly completeness by reporting the presence/absence of expected core genes. Finally, MultiQC is used to compile results from each of these programs into a single, comprehensive report, presenting quality control data for all samples in a consistent and well-organized format (Ewels et al. 2016).

Additional user-friendly features

PathogenSurveillance incorporates extensive parallelization, error recovery mechanisms, and caching of intermediate results, enabling improved efficiency and resilience in automated execution of large-scale, long-running analyses. Parallel processing occurs as system resources and API limits allow. In HPC clusters and commercial clouds, this can scale to hundreds or thousands of jobs running in parallel, each using all available central processing units (CPUs) on its assigned node or virtual machine. Processes that encounter errors are automatically retried a set number of times, with each attempt incrementally increasing Random Access Memory (RAM) and CPU allocation to accommodate resource demands. Processes that communicate with external web services will pause before retrying after a failed attempt, allowing time for temporary network issues to resolve. Information about pipeline execution, including any warnings or errors encountered during the process, are presented in output reports.
Caching of intermediate results by *PathogenSurveillance* offers three key advantages. First, if the pipeline terminates prematurely either due to an excessive number of failed processes or a

user-issued command, it can be restarted from the point at which it stopped. This is made possible by using the "-resume" option. Second, caching gives users opportunities to incorporate additional data or adjust parameters, without requiring extensive computing time. Only the affected portions of the analysis are recomputed and as a result, rerun executions are dramatically faster. Third, and similarly, caching enables users to iteratively refine evolutionary and population-level analyses. Users can first run *PathogenSurveillance* without specifying references, relying exclusively on automated selection, and then manually choosing more appropriate references after inspecting results. Reruns will be executed quickly and potentially be more robust. A drawback of caching is its large storage footprint, as seen in other comprehensive pipelines such as *Bactopia* (Petit and Read 2020b). We mitigated this to some extent by designing the pipeline to avoid storing redundant intermediate results.

Validation of PathogenSurveillance with published data

We evaluated published or custom datasets for accuracy and performance of *PathogenSurveillance*. The first dataset, used to test the accuracy of automated phylogenetic inference, is diverse and originally developed for a phylogenomic analysis of the *Serratia* genus (Williams et al. 2022). In previous work, authors used two methods to quality control sequence data and used two different methods to assemble long-read PacBio and short-read Illumina data. The pipeline was executed with the following command:

```
nextflow run nf-core/PathogenSurveillance -r 1.0.0 -resume -
profile docker,serratia_full --outdir serratia_results
```

Phylogenetic groups were further refined by using ANI clustering. Congruence between phylogenic trees was visualized using cophylogeny plots generated by the R package phytools (Revell 2024), ape (Paradis et al. 2004), phangorn (Schliep 2011), and ggtree (Yu et al. 2017).

From the original set of 664 samples, we manually selected a subset of 302 that captured the species and ecological diversity of the full set (Supplementary Table 2). The subset represented 11 species identified previously, with sequencing reads generated using long- and short-read technologies. We input their accession numbers and metadata into a TSV file. We also manually selected accessions of reference assemblies that were previously selected (Williams et al. 2022). The pipeline was executed with a single line command and in a mode that prevents *PathogenSurveillance* from automatically identifying and retrieving additional reference assemblies. *PathogenSurveillance* generated a phylogenetic tree, along with all the other associated intermediate assemblies, annotations, and ortholog cluster files as well as quality control metrics. The resulting tree was concordant in topology to the core gene phylogeny previously reported, and importantly, the species and lineage assignments were highly similar between the two analyses, with minor discrepancies restricted to placements within clonal lineages (Figure 3) (Williams et al. 2022). Overall, evaluation of this test dataset demonstrates that *PathogenSurveillance* can reliably generate phylogenetic and taxonomic insights with minimal user input.

Performance

Lastly, we generated prokaryotic and eukaryotic datasets to evaluate the impact of sample and genome sizes on runtime and RAM usage. One dataset was derived from a study of *Klebsiella pneumoniae*, which has an average genome size of 5.7 Mb (David et al. 2020)(Supplementary Table 4). To evaluate the effect of sample size, we randomly selected samples to form runs of 1, 3, 5, 10, 25, 50, 75, 100, 150, and 200 samples. The pipeline was executed with caching disabled to analyze three replicates of each of the runs. As expected, runtime showed a linear increase from 0.4 to 11.7 hours as the number of samples increased from 1 to 200 samples (Figure 4A). RAM also increased linearly from 4.3 GB for 1 sample to 12.2 GB for 200 samples (Figure 4B).

We also created a dataset of taxonomically disparate organisms with genome sizes that vary from 2.1 Mb to 224.8 Mb (David et al. 2020)(Supplementary Table 5). Each dataset was composed of three samples of a single species and was run in triplicate. Each consists of Illumina paired-end reads, which were subset to 25x coverage for prokaryotes and 50x for eukaryotes. The results for prokaryotes and eukaryotes are displayed in different colors because they are processed by different workflow branches (Figure 1). Prokaryotes, regardless of genome size, were each completed in less than one hour of automated analyses (Figure 4C) with RAM usage less than 15.0Gb (Figure 4D). In contrast, the runtime for eukaryotic genomes had a substantial range that scaled linearly to genome size. The largest genome took 13.6 hours of runtime. RAM usage ranged between 6.0 GB and 70.0 GB for the eukaryotic dataset.

All tests were run on a System 76 Thelio Major Linux Desktop with a Ryzen 9 7950x 16-core processor.

Discussion

Pests and pathogens can emerge and rapidly adapt, often evading detection by traditional biosurveillance methods (Korber et al. 2020). In response to these challenges, we developed *PathogenSurveillance,* a user-friendly computational workflow for analyzing WGS data, with features specific for pest and pathogen detection. *PathogenSurveillance* provides a computational workflow that is highly portable for implementation on any Linux cloud or workstation. Our implementation follows the FAIR principles. Importantly, the pipeline can work with known or unknown taxa and can resolve clonality or novel variants if WGS data is available for the clades in question.

A key design principle of *PathogenSurveillance* is its commitment to lowering the barrier to entry and accelerating the analyses of WGS data. Population-level analysis requires domain specific knowledge in molecular evolution and bioinformatics, particularly for selecting appropriate references, installing software and dependencies, and constructing robust phylogenies. At its core, *PathogenSurveillance* is a generalizable population genomics pipeline, featuring a rules-based system that automates reference selection. Leveraging the Nextflow workflow management system, this design empowers users from diverse backgrounds, including those without formal training in molecular evolution and bioinformatics, to effectively analyze WGS data. Additionally, the organization of results reflects a deliberate design intended to support further in-depth investigations, both through manual and automated approaches. Collectively, *PathogenSurveillance* provides a streamlined and accessible framework for automating initial population genomic analysis, supporting both applied and fundamental

research applications.

There are constraints to *PathogenSurveillance* that should be considered. First, the pipeline does not support analyses of viruses, as they would require their own workflow branch to parse metagenomic data and employ specialized approaches for taxonomic identification (Rangel-Pineros et al. 2023). Second, the accuracy in which the pipeline predicts taxonomic identities is constrained by the contents of databases used and the correctness of the taxonomic names they contain. Third, *PathogenSurveillance* was designed for WGS data derived from cultured organisms, which may limit applicability to metagenomic or environmental samples. Fourth, *PathogenSurveillance* employs default parameters across all steps, which may require appropriate adjustments for non-standard cases or refining reference selection. Finally, the pipeline can be computationally demanding. While the Nextflow framework allows efficient memory allocation per task, certain processes and samples may require substantial memory. Moreover, the pipeline generates numerous intermediate files, requiring storage capacity that is approximately five times greater than the size of input files.

Nonetheless, there are ways to apply *PathogenSurveillance* that mitigate these constraints. For example, we have identified contaminating reads in some sample datasets. When left unfiltered, the pipeline successfully resolved taxonomic identities and generated corresponding phylogenetic trees for both the primary and contaminating samples.. Regarding use of default parameters, caching gives users the flexibility of running the pipeline with a preliminary assessment and rerunning it with refined parameters or references without repeating the entire analysis. This not only saves considerable time but also supports reproducibility through automated, consistent execution. To mitigate storage requirements, users can clear the cache after analysis. However, for taxa that are repeatedly analyzed, retaining cached results may be advantageous, as it offsets rerun times.

In summary, *PathogenSurveillance* is executed with a single command line to automate the analyses of WGS data. It enhances traditional diagnostic approaches by improving analytical resolution and enriching the data available for more robust interpretation. It can also aid in identifying novel or emerging pathogens as well as place variants within taxa. These features underscore the potential of *PathogenSurveillance* in being a platform for consideration in global pathogen and pest biosurveillance (Carvajal-Yepes et al. 2019; Weisberg et al. 2021).

Data availability

PathogenSurveillance is free and open source under the MIT license. The source code is hosted on Github (https://github.com/nf-core/*PathogenSurveillance*) and documentation is available on nf-core (https://nf-co.re/*PathogenSurveillance*/). All data used in the validation of the pipeline presented here are available in the test data repository on GitHub (https://github.com/nf-core/test-datasets/tree/*PathogenSurveillance*). The scripts and input data used to create figures in this manuscript are also available on GitHub (https://github.com/grunwaldlab/*PathogenSurveillance*_publications).
Various test datasets automatically downloaded from NCBI of varying complexity available as profiles can easily be run as documented at https://github.com/nf-core/test-datasets/tree/*PathogenSurveillance*.

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Author Contributions

ZSLF designed and implemented nf-core/*PathogenSurveillance*. MAS, CPR, LKB, FIB, AJW, and HP contributed scripts and modules, and/or enhanced or tested pipeline reliability, usability and performance. ZSLF, MAS, CPR, JHC, and NJG wrote the manuscript, with input from all authors. NJG and JHC led the conceptualization and planning of nf-core/*PathogenSurveillance*, supervised its development, and secured funding.

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Figures

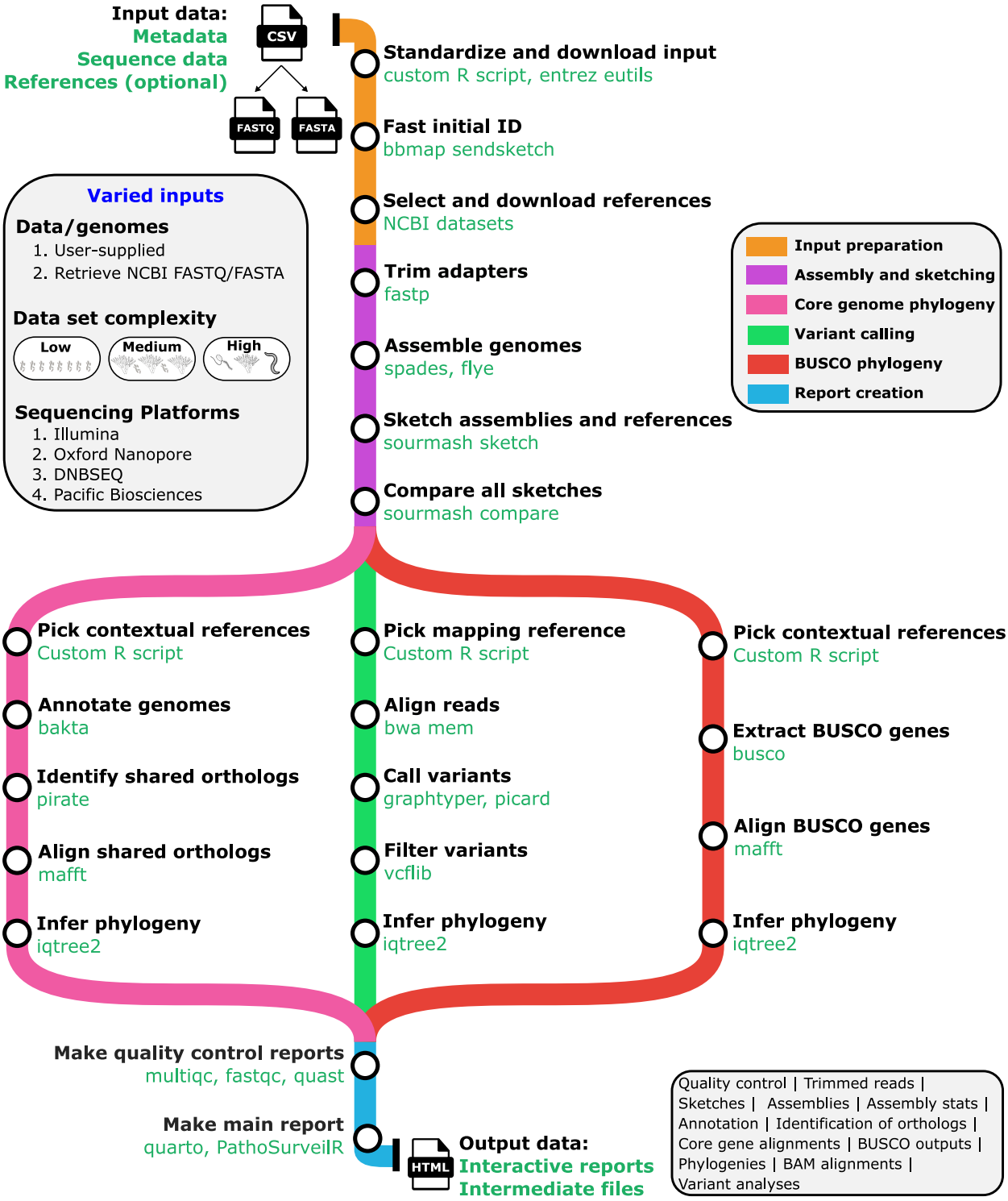

Figure 1. *PathogenSurveillance* automates comprehensive analysis of prokaryotic and eukaryotic whole genome sequencing data. A TSV file indicating paths or URLs to FASTQ or

FASTA files of short or long read sequencing data initiates the process of downloading and formatting of input files and references. The next part of the main branch quality controls sequencing reads and generates assemblies as well as *k*-mer sketches. It then diverges into three branches. The left branch is for samples of prokaryotic origin and will generate core phylogenies based on all shared orthologous gene sequences and variants, respectively, for each group of related samples. The right branch is for samples of eukaryotic origin and will build a phylogenetic tree for each group of related samples based on shared, single-copy BUSCO gene sequences. The middle branch creates SNP phylogenies for both prokaryotic and eukaryotic samples. Finally, the branches converge and *PathogenSurveillance* will generate a final HTML report with interactive plots and tables as well as quality control reports. Prominent steps in the workflow are printed in black beside each node with select corresponding tools used printed below in green.

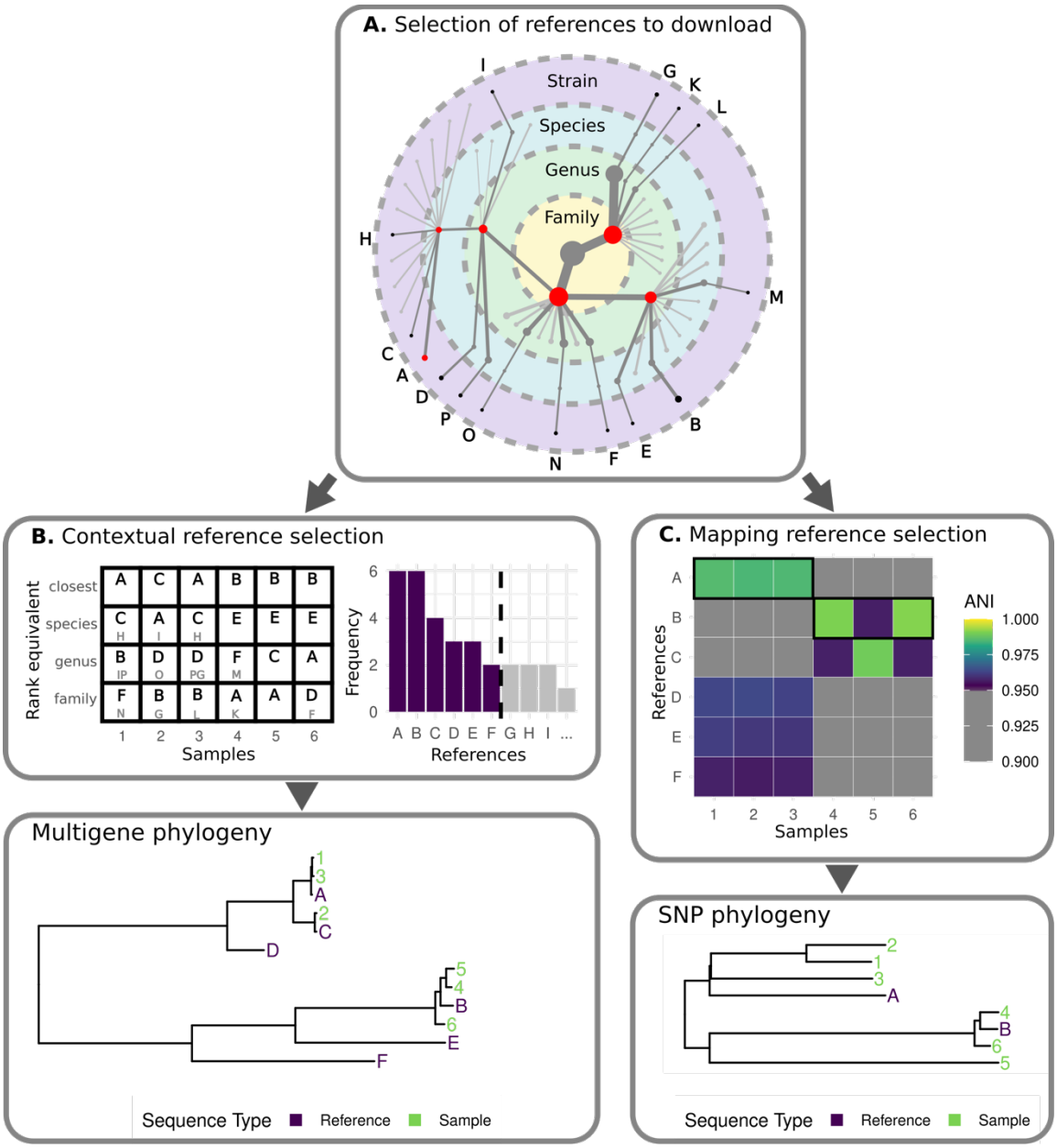

Figure 2. *PathogenSurveillance* automates reference selection for phylogenetic analyses. Shown is a hypothetical example illustrating sampling of genomes from **(A)** publicly available references for **(B)** multigene phylogenies and **(C)** SNP-based phylogenies or minimum spanning networks, respectively. **(A)** First, *PathogenSurveillance* compares *k*-mer sketches of raw reads to sketches of all NCBI RefSeq assemblies using BBmap sendsketch. Taxa likely present in samples are identified based on match similarity metrics (shown as red nodes in the taxonomic tree in (**A**) and representative assemblies of subtaxa are downloaded for each detected taxon (black nodes). The pipeline prioritizes enrichment of candidate references from more closely related taxa but also includes more distant taxa in case the initial identification was incorrect. **(B)** From the set of references downloaded a subset are selected to provide context for multi-gene phylogenetic trees based on pairwise ANI estimates between samples and references. References estimated to be most similar to each sample are always included in addition to a minimal set of

references selected for the set of samples as a whole that occur at a range of similarities to each sample. Each cell in the matrix represents a role that references can fit into. References are ordered by how many cells each can fill, as is shown in the histogram, and selected in this order until all cells are filled. **(C)** Mapping references are also selected for SNP calling based on estimated ANI values. A conceptual heatmap illustrates pairwise ANI comparisons, with cells exceeding the minimum threshold required shown in color. The reference with an estimated ANI exceeding a threshold for the most samples is chosen and this process is repeated until all samples have an assigned reference. Ties are broken based on mean ANI. A conceptual SNP-based phylogenetic tree demonstrates that only clusters with mapping references A and B met the minimum group size criteria for SNP calling and phylogenetic inference.

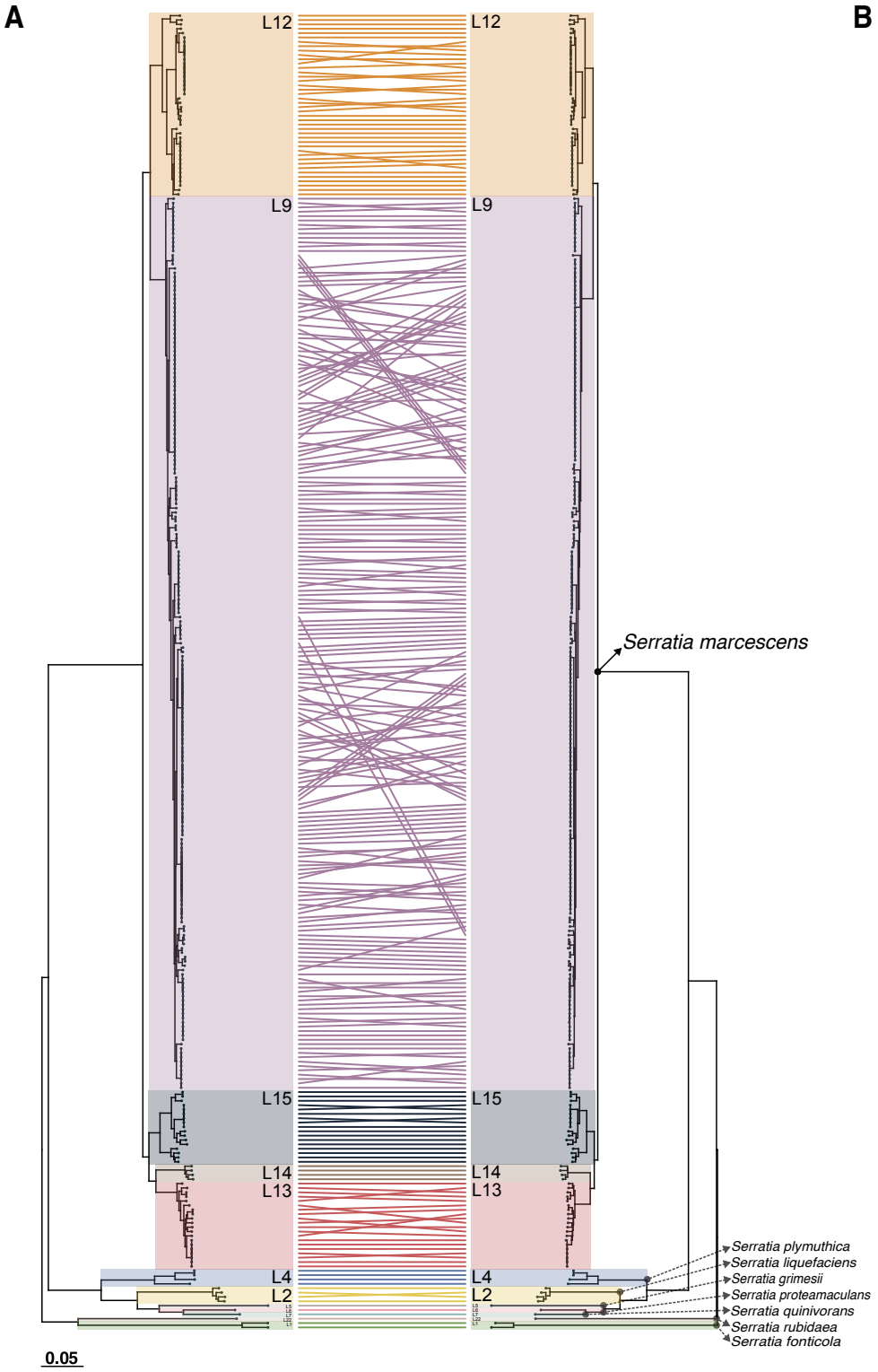

Figure 3. *PathogenSurveillance* core genome phylogeny reproduces a previously published phylogeny fully resolving species and lineages. The tanglegram shows congruence between (**A**) a maximum likelihood core gene phylogeny generated by *PathogenSurveillance*, and (**B**) a phylogeny reproduced from the literature. Matched samples are linked across trees by lines, with color-coding denoting lineage assignments. Major species and lineages (L#) are labeled as

published. Scale bars represent the number of nucleotide substitutions per site. See narrative for reference citation.

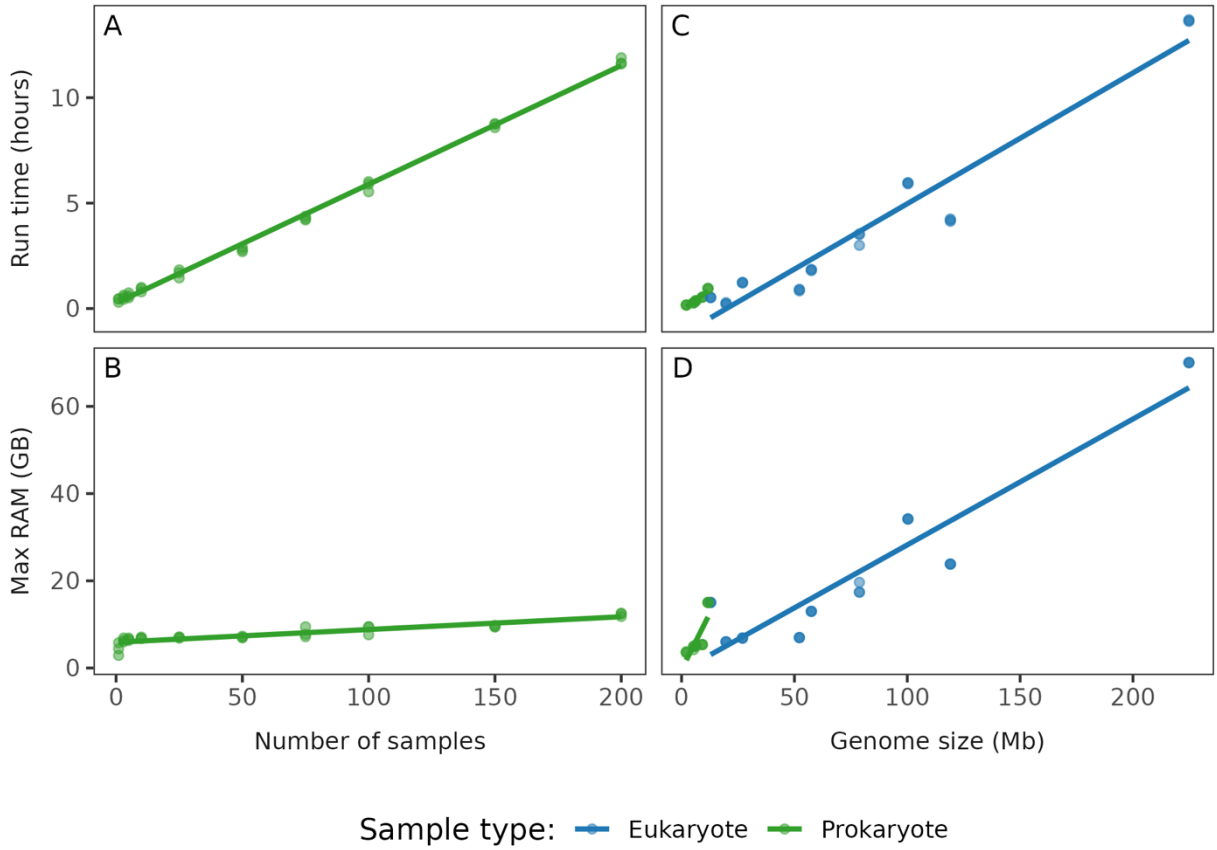

Figure 4. *PathogenSurveillance* demonstrates linear and scalable performance across a wide range of sample and genome sizes. Two test datasets were used to evaluate how the RAM and runtime of the pipeline scaled with number of samples and genome size. (**A**) and (**B**) show results for datasets increasing in sample sizes, while (**C**) and (**D**) show results for datasets with increasing genome sizes. Runtime (in clock hours) is plotted in (**A**) and (**C**), and maximum random-access memory (RAM) usage (in gigabytes (GB)) is plotted in (**B**) and (**D**). For genome size tests, each data set consisted of three samples of a given species and eukaryotes and prokaryotes are summarized separately since they are analyzed with different methods. Each dataset was analyzed in triplicate by *PathogenSurveillance*.

Supplementary data

```
output_directory
├── aligned_reads
│   ├── <reference_id>--<sample_id>.bam                                  : Unfiltered read alignements to references in BAM format
│   ├── <reference_id>--<sample_id>.formatted.bam                        : Quality filtered read alignements to references in BAM format
│   ├── <reference_id>--<sample_id>.formatted.bam.csi                    : Index for the filtered BAM files produced by samtools index
│   └── <reference_id>--<sample_id>.formatted.MarkDuplicates.metrics.txt : Output from picard MarkDuplicates containing summary data tables
├── annotations
│   └── <method>
│       ├── <sample_id>.embl                                             : Genome annotations and sequences in (multi) EMBL format
│       ├── <sample_id>.faa                                              : CDS/ORF amino acid sequences in FASTA format
│       ├── <sample_id>.ffn                                              : Feature nucleotide sequences in FASTA format
│       ├── <sample_id>.fna                                              : Replicon/contig DNA sequences in FASTA format
│       ├── <sample_id>.gbff                                             : Annotations of genomes in (multi) GenBank format
│       ├── <sample_id>.gff3                                             : Annotations of genomes in GFF3 format
│       ├── <sample_id>.hypotheticals.faa                                : Hypothetical protein CDS amino acid sequences in FASTA format
│       ├── <sample_id>.hypotheticals.tsv                                : Information on hypothetical protein CDSs in TSV format
│       ├── <sample_id>.tsv                                              : Information for protein CDSs in TSV format
│       └── <sample_id>.txt                                              : Genome annotation summary statistics in plain text format
├── assemblies
│   ├── flye
│   │   ├── <sample_id>.assembly_graph.gfa.gz                            : Genome assembly graphs in gzipped GFA format
│   │   ├── <sample_id>.assembly_graph.gv.gz                             : Genome assembly in gzipped Graphviz format
│   │   ├── <sample_id>.assembly_info.txt                                : Statistics on contigs produced by Flye in TSV fomrat
│   │   ├── <sample_id>.assembly.fasta.gz                                : Genome assemblies in gzipped FASTA format
│   │   ├── <sample_id>.flye.log                                         : Log file produced by Flye in plain text format
│   │   └── <sample_id>.params.json                                      : Parameters used to run Flye in JSON format
│   └── spades
│       ├── <sample_id>.assembly.gfa.gz                                  : Genome assembly graphs in gzipped GFA format
│       ├── <sample_id>.scaffolds.fa.gz                                  : Genome assemblies in gzipped FASTA format
│       ├── <sample_id>.spades.log                                       : Log file produced by Spades in plain text format
│       └── <sample_id>.warnings.log                                     : Warnings produced by Spades in plain text format
├── busco
│   ├── <sample_id>--<database>-busco                                    : BUSCO output directory
│   ├── <sample_id>--<database>-busco.batch_summary.txt                  : BUSCO analysis summary statistics in TSV format
│   └── <sample_id>--<database>-busco.log                                : Log file produced by BUSCO in plain text format
├── downloads
│   ├── annotations
│   │   └── <reference_id>.gff.gz                                        : Genome annotations downloaded by the pipeline in gzipped GFF format
│   ├── assemblies
│   │   └── <reference_id>.fasta.gz                                      : Genome assemblies downloaded by the pipeline in gzipped FASTA format
│   └── reads
│       └── <reference_id>_<orientation>.fastq.gz                        : Reads downloaded by the pipeline in gzipped FASTQ format
├── fastp
│   ├── <sample_id>.fastp.html                                           : FASTP report with read quality and adapter trimming statistics in HTML format
│   ├── <sample_id>.fastp.json                                           : FASTP report with read quality and adapter trimming statistic in JSON format
│   └── <sample_id>.fastp.log                                            : Log file produced by FASTP
├── metadata
│   ├── reference_metadata.tsv                                           : Reference metadata in TSV format
│   └── sample_metadata.tsv                                              : Sample metadata in TSV format
├── pipeline_info
│   ├── execution_report_<date>.html                                     : Statistics like time and ram usage for pipeline execution as a HTML report
│   ├── execution_trace_<date>.txt                                       : Statistics like time and ram usage for pipeline execution in TSV format
│   ├── messages.tsv                                                     : Errors, warnings, and messages produced by the pipeline in TSV format
│   ├── params_<date>.json                                               : Parameters used when running the pipeline in JSON format
│   ├── pathogensurveillance_run_info.yml                                : Pipeline run metadata in YML format
│   ├── pipeline_dag_<date>.html                                         : Flowchart of the pathogensurveillance pipeline automatically generated by Nextflow
│   └── version_info.yml                                                 : Versions of software used in the pipeline in YML format
├── pirate
│   └── <report_id>_results                                              : Pirate output directory with gene orthology information
├── pocp
│   └── <report_id>_pocp.tsv                                             : Percentage of conserved proteins in TSV format
├── quality_control
│   ├── fastqc
│   │   ├── <reads_id>_fastqc.html                                       : FastQC report on read quality in HTML format
│   │   └── <reads_id>_fastqc.zip                                        : Zipped directory of FastQC output
│   ├── multiqc
│   │   └── <report_id>_multiqc                                          : Directory of MultiQC output with intermediate files used to make the MultiQC report
│   │       └── multiqc_report.html                                      : MultiQC report combining the summary quality control output in HTML format
│   ├── nanoplot
│   │   ├── <sample_id>_nanoplot-report.html                             : Nanoplot report on read quality in HTML format
│   │   └── <sample_id>_NanoStats.txt                                    : Nanoplot report on read quality in plain text format
│   └── quast
│       ├── <sample_id>.tsv                                              : Quast summary statistics on genome assembly quality in headerless TSV format
│       └── <sample_id>
│           └── report.html                                              : Quast report with data on genome assembly quality in HTML format
├── reference_data
│   ├── considered
│   │   └── <taxon_id>.tsv                                               : Metadata of available assemblies on NCBI in TSV format
│   ├── downloaded
│   │   └── <sample_id>.tsv                                              : Metadata of references selected for download from NCBI in TSV format
│   └── selected
│       ├── <report_id>_busco_references.tsv                             : IDs of references selected for multigene phylogenies in TSV format
│       ├── <report_id>_core_references.tsv                              : IDs of references selected for multigene phylogenies in TSV format
│       └── <report_id>_mapping_references.tsv                           : IDs of references selected for multigene phylogenies in TSV format
├── reports
│   └── <report_id>_pathsurveil_report.html                              : Primary report for pathogensurveillance in HTML format
├── sendsketch
│   └── <sample_id>.txt                                                  : Table returned by BBmap sendsketch with initial identifications in TSV format
├── shared_genes
│   └── <method>
│       └── <gene_id>.aligned.fas                                        : Aligned sequences for each gene shared amoung a group of organisms in FASTA format
├── sketch_comparisons
│   ├── ani_matricies
│   │   └── <report_id>_comp.csv                                         : Estimated ANI similarity matrix made by sourmash compare in CSV format
│   └── sketches
│       └── <id>.sig                                                     : FracMinHash signature of the given sequence made by sourmash sketch in JSON
├── trees
│   ├── busco
│   │   └── <report_id>--<cluster_id>.treefile                           : Trees infered from multigene phylogeny in Newick format
│   ├── core
│   │   └── <report_id>--<cluster_id>.treefile                           : Trees infered from multigene phylogeny in Newick format
│   └── snp
│       └── <report_id>--<reference_id>.treefile                         : Trees inferred from variant analysis in Newick format
└── variants
    ├── <report_id>--<reference_id>.fasta                                : Filtered variants in FASTA format
    ├── <report_id>--<reference_id>.vcf.gz                               : Unfiltered variants in VCF format
    └── <report_id>--<reference_id>.vcffilter.vcf.gz                     : Filtered variants in VCF format
```

Supplementary Figure 1. *PathogenSurveillance* organizes and names output files for further analyses. The left side displays the hierarchical structure of output files. Angle brackets (<>) show run specific identifiers for references, samples, and reports. The right side provides brief descriptions of each file type, highlighting their applications in downstream analyses.

Supplementary Table 1. Modules and module updates contributed to nf-core as part of the PathogenSurveillance pipeline development.

Nf-core module	**Status**	**Actions**
`bbmap/sendsketch`	New	Added new module
`busco/download`	New	Added new module
`graphtyper/genotype`	New	Added new module
`graphtyper/vcf_concatenate`	New	Added new module
`khmer/trimlowabund`	New	Added new module
`seqkit/head`	New	Added new module
`vcflib/vcffilter`	New	Added new module
`busco/busco`	Update	Added single copy sequence files to the usable output files
`gatk4/variantfiltration`	Update	Allowed for the use of compressed reference files
`iqtree`	Update	Allowed for the use of multiple input alignments
`pirate`	Update	Allowed for the use of GFF3 files and updated dependencies
`sourmash/compare`	Update	Modified script to name output by prefix and updated dependencies
`sourmash/gather`	Update	Created new unit tests
`sourmash/taxannotate`	Update	Created new unit tests
`tabix/bgzip`	Update	Made index file parameter detection more robust

Supplementary Table 2. Accessions of the *Serratia* genus with both long-read Nanopore and short-read Illumina data used for validation of the *PathogenSurveillance* pipeline from (Williams et al. 2022).

Sample	NCBI accession	BioProject	Lineage	Phylogroup	Sequence type
1	SRR3927533	PRJNA60453	4	8	Illumina
2	SRR3927534	PRJNA60457	4	8	Illumina
3	SRR3926812	PRJNA178957	22	11	Illumina
4	SRR3927990	PRJNA61833	7	1	Illumina
5	SRR3925616	PRJNA175925	4	8	Illumina
6	SRR5629779	PRJNA246471	12	2	Nanopore
7	SRR2059988	PRJNA286707	13	2	Illumina
8	SRR1655333	PRJNA267549	12	2	Illumina
9	SRR1655414	PRJNA267549	9	2	Illumina
10	SRR1655439	PRJNA267549	13	2	Illumina
11	SRR1655440	PRJNA267549	13	2	Illumina
12	SRR1655376	PRJNA267549	15	2	Illumina
13	SRR1655391	PRJNA267549	9	2	Illumina
14	SRR1655415	PRJNA267549	9	2	Illumina
15	SRR1655375	PRJNA267549	15	2	Illumina
16	SRR1655390	PRJNA267549	9	2	Illumina
17	SRR1655624	PRJNA267549	2	4	Illumina
18	SRR1655701	PRJNA267549	15	2	Illumina
19	SRR1655706	PRJNA267549	15	2	Illumina
20	SRR1655712	PRJNA267549	15	2	Illumina
21	SRR1655833	PRJNA267549	13	2	Illumina
22	SRR1655844	PRJNA267549	13	2	Illumina
23	SRR1655713	PRJNA267549	15	2	Illumina
24	SRR1655716	PRJNA267549	15	2	Illumina
25	SRR1655733	PRJNA267549	15	2	Illumina
26	SRR1655793	PRJNA267549	13	2	Illumina
27	SRR1655797	PRJNA267549	13	2	Illumina
28	SRR1655818	PRJNA267549	13	2	Illumina
29	SRR1655820	PRJNA267549	13	2	Illumina
30	SRR1655878	PRJNA267549	13	2	Illumina
31	SRR1655960	PRJNA267549	15	2	Illumina
32	SRR1655976	PRJNA267549	15	2	Illumina
33	SRR1656119	PRJNA267549	12	2	Illumina
34	SRR1656133	PRJNA267549	9	2	Illumina
35	SRR1656143	PRJNA267549	9	2	Illumina

36	SRR1656234	PRJNA267549	9	2	Illumina
37	SRR1656346	PRJNA267549	12	2	Illumina
38	ERR486640	PRJEB5065	9	2	Illumina
39	ERR486562	PRJEB5065	9	2	Illumina
40	ERR486664	PRJEB5065	9	2	Illumina
41	ERR486618	PRJEB5065	9	2	Illumina
42	ERR486619	PRJEB5065	9	2	Illumina
43	ERR486680	PRJEB5065	9	2	Illumina
44	ERR486558	PRJEB5065	9	2	Illumina
45	ERR486565	PRJEB5065	9	2	Illumina
46	ERR486521	PRJEB5065	9	2	Illumina
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Supplementary Table 4. Genbank accessions of *Klebsiella pneumoniae*. The associated Illumina reads were processed by the *PathogenSurveillance* pipeline for validation used in Figure 4A, B.

Sample_ID	NCBI accession	Bioproject	Species	Kingdom	Sequence type
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Supplementary Table 5. Genbank accessions of samples belonging to both prokaryotes and eukaryotes. The associated reads were processed by the *PathogenSurveillance* pipeline for validation used in Figure 4C, D.

Sample_ID	NCBI SRA accession	Bioproject	Species	Kingdom	Sequence type
Celg1	SRR28479892	PRJNA1091400	*Caenorhabditis elegans*	Anamalia	Illumina
Celg2	SRR28479941	PRJNA1091400	*Caenorhabditis elegans*	Anamalia	Illumina
Celg3	SRR28479942	PRJNA1091400	*Caenorhabditis elegans*	Anamalia	Illumina
Brady1	SRR17382571	PRJNA793169	*Bradyrhizobium japonicum*	Bacteria	Illumina
Brady2	SRR17382844	PRJNA793169	*Bradyrhizobium japonicum*	Bacteria	Illumina
Brady3	SRR17388438	PRJNA793169	*Bradyrhizobium japonicum*	Bacteria	Illumina
Limo1	ERR12342572	PRJEB70875	*Limosilactobacillus fermentum*	Bacteria	Illumina
Limo2	SRR18850315	PRJNA830347	*Limosilactobacillus fermentum*	Bacteria	Illumina
Limo3	SRR18850317	PRJNA830347	*Limosilactobacillus fermentum*	Bacteria	Illumina
Pseudo1	SRR33648670	PRJNA1225923	*Pseudomonas aeruginosa*	Bacteria	Illumina
Pseudo2	SRR32466794	PRJNA1225923	*Pseudomonas aeruginosa*	Bacteria	Illumina
Pseudo3	SRR33648579	PRJNA1225923	*Pseudomonas aeruginosa*	Bacteria	Illumina
Solivo1	SRR9661589	PRJNA553182	*Streptomyces olivochromogenes*	Bacteria	Illumina
Solivo2	SRR9661590	PRJNA553182	*Streptomyces olivochromogenes*	Bacteria	Illumina
Solivo3	SRR9661593	PRJNA553182	*Streptomyces olivochromogenes*	Bacteria	Illumina
Xan1	SRR28281444	PRJNA991976	*Xanthomonas hortorum pv pelargonii*	Bacteria	Illumina
Xan2	SRR28281445	PRJNA991976	*Xanthomonas hortorum pv pelargonii*	Bacteria	Illumina
Xan3	SRR28281439	PRJNA991976	*Xanthomonas hortorum pv pelargonii*	Bacteria	Illumina
Fus1	SRR21509025	PRJNA878477	*Fusarium oxysporum f sp niveum*	Fungi	Illumina
Fus2	SRR21509023	PRJNA878477	*Fusarium oxysporum f sp niveum*	Fungi	Illumina
Fus3	SRR21509022	PRJNA878477	*Fusarium oxysporum f sp niveum*	Fungi	Illumina
Umay1	SRR12990819	PRJNA674756	*Ustilago maydis*	Fungi	Illumina
Umay2	SRR12990820	PRJNA674756	*Ustilago maydis*	Fungi	Illumina
Umay3	SRR12990821	PRJNA674756	*Ustilago maydis*	Fungi	Illumina
Athal1	SRR21871460	PRJNA887677	*Arabidopsis thaliana*	Plantae	Illumina

Athal2	SRR21871466	PRJNA887677	*Arabidopsis thaliana*	Plantae	Illumina
Athal3	SRR21871467	PRJNA887677	*Arabidopsis thaliana*	Plantae	Illumina
Csativus1	SRR25709139	PRJNA1007410	*Cucumis sativus*	Plantae	Illumina
Csativus2	SRR25709141	PRJNA1007410	*Cucumis sativus*	Plantae	Illumina
Csativus3	SRR25709138	PRJNA1007410	*Cucumis sativus*	Plantae	Illumina
Otauri1	ERR5417781	PRJEB43294	*Ostreococcus tauri*	Protista	Illumina
Otauri2	ERR5417780	PRJEB43294	*Ostreococcus tauri*	Protista	Illumina
Otauri3	ERR5417779	PRJEB43294	*Ostreococcus tauri*	Protista	Illumina
Plas1	SRR32867107	PRJNA1242290	*Plasmodium vivax*	Protista	Illumina
Plas2	SRR32867100	PRJNA1242290	*Plasmodium vivax*	Protista	Illumina
Plas3	SRR32867098	PRJNA1242290	*Plasmodium vivax*	Protista	Illumina
Pcap1	SRR13176614	PRJNA481983	*Phytophthora capsici*	Stramenopila	Illumina
Pcap2	SRR8259121	PRJNA505815	*Phytophthora capsici*	Stramenopila	Illumina
Pcap3	SRR5944957	PRJNA386483	*Phytophthora capsici*	Stramenopila	Illumina
Pram1	SRR16939097	PRJNA780196	*Phytophthora ramorum*	Stramenopila	Illumina
Pram2	SRR16939100	PRJNA780196	*Phytophthora ramorum*	Stramenopila	Illumina
Pram3	SRR16939107	PRJNA780196	*Phytophthora ramorum*	Stramenopila	Illumina