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KATERYNA PANTIUKH

From sequences to knowledge: challenges and opportunities of genome-resolved metagenomics

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From sequences to knowledge: challenges and opportunities of genome-resolved metagenomics

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Institute of Genomics, University of Tartu, Estonia

This dissertation is accepted for the commencement of the degree of Doctor of Philosophy in Genomics on June 8, 2026, by the Council of the Institute of Genomics, University of Tartu.

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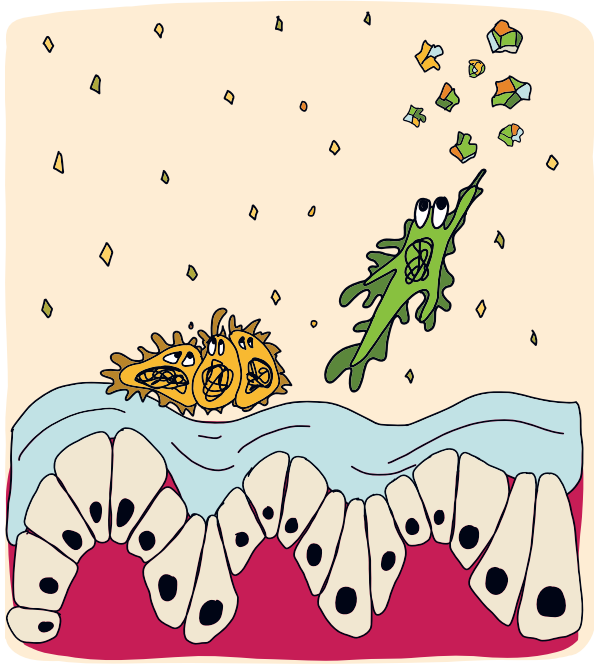

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, referred to in the text by Roman numerals (Ref. I to Ref. III):

I Kinga Zielińska*, **Kateryna Pantiukh*,** Paweł P Łabaj, Tomasz Kosciolek, Elin Org "A large-scale comparative metagenomic analysis of short-read sequencing platforms indicates high taxonomic concordance and functional analysis challenges." mSystems, DOI: 10.1128/msystems.01714-25. https://journals.asm.org/doi/10.1128/msystems.01714-25

II **Pantiukh, Kateryna**; Aasmets, Oliver; Krigul, Kertu Liis; Org, Elin (2026). Metagenome-assembled genomes from a population-based cohort uncover novel gut species and within-species diversity, revealing prevalent disease associations, mSystems 2024.07.06.602324. https://journals.asm.org/doi/10.1128/msystems.00114-26

III **Pantiukh, Kateryna**, and Elin Org. "Human gut archaea collection from Estonian population." Scientific data vol. 13,1 366. 6 Feb. 2026, doi:10.1038/s41597-026-06742-1. https://www.nature.com/articles/s41597-026-06742-1

***** These authors contributed equally

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My contributions to the listed publications were as follows:

Ref. I Created the study design, performed the taxonomic profiling, interpreted the results, prepared figures and tables, wrote the manuscript, and participated in the critical review of the paper.

Ref. II Helped with the study design, created the study questions, reconstructed the MAGs, created study hypotheses, interpreted the results, prepared the figures, uploaded MAGs to ENA, participated in discussions, wrote the original manuscript, and participated in the critical review of the paper.

Ref. III Reconstructed the MAGs and created the archaea MAG database, uploaded the data to ENA, wrote the original manuscript, and participated in the critical review of the paper.

LIST OF ABBREVIATIONS

MAG	Metagenome assembled genome
SAG	Single-amplified genome
ncMAG	Near-complete MAG
repMAG	Representative MAG for species
GRM	Genome resolved metagenomics
EstMB	Estonian microbiome cohort
EstMB-deep	Estonian microbiome deep cohort
EstMB-allMAG	Estonian collection of all reconstructed MAGs
EstMB-repMAG	Estonian collection of species representative MAGs
ANI	Average nucleotide identity
GU	Genome unit
GUN	Genome unit number
nGUN	Normalised genome unit number
MWAS	Microbiome wide association study
MIMAG	Minimum Information about a Metagenome-Assembled Genome
MISAG	Minimum Information about a Single Amplified Genome
FISH	Fluorescence in situ hybridization
qPCR	Quantitative polymerase chain reaction

INTRODUCTION

It's hard to grasp both the importance of microorganisms in our lives and their differences from the macro world we've grown accustomed to.

Bacteria and archaea are closely linked to human health. In the gut, they can benefit the host by expanding metabolic capacity, degrading otherwise indigestible dietary compounds, producing metabolites that regulate immunity, and helping protect against invading pathogens. At the same time some microbial activities may erode the colonic mucus barrier or generate harmful molecules associated with inflammation and disease. Despite this recognized importance, we still do not fully understand the mechanisms by which gut microbes influence host health.

Recent advances in genome-resolved metagenomics have transformed microbiome research by enabling the reconstruction of microbial genomes directly from complex communities. With this approach, massive resources have been created, including thousands of metagenome-assembled genomes that have revealed species that were previously unknown along with extensive diversity within species that were already known. Genome-resolved metagenomics therefore provides an opportunity not only to expand microbial reference catalogues, but also to refine how microbiome variation is detected, interpreted and linked to host phenotypes. It provides an opportunity to revisit key concepts in microbiology, including how bacterial species and subspecies-level entities should be defined. In the coming years, genome-resolved metagenomics is likely to bring a new level of understanding of the microbiome and its connection to human health.

However, several important challenges remain. Population-based microbiome studies often combine sequencing data generated on different platforms, making it necessary to evaluate whether platform-specific effects influence taxonomic and functional profiling. Second, global reference databases may not fully capture population-specific microbial diversity, potentially limiting the detection of taxa that are common in particular cohorts but underrepresented in existing catalogues. Third, species-level profiling may obscure biologically relevant within-species variation that may be important for understanding microbiome-host associations.

In this thesis, I use a cohort of 2,504 volunteers from Estonia, including two datasets generated with moderate and deep sequencing, to explore the potential and limitations of current genome-resolved metagenomics in revealing connections between the microbiome and human health. In the first part of the thesis, I show that different sequencing platforms provide comparable microbiome community profiles and can therefore be combined within a single study, although functional profiling is more sensitive to platform-related differences than taxonomic profiling. Second, I demonstrate that population-specific metagenome assembly can reveal new information about both species-level and within-species diversity. Finally, I integrated microbiome profiles with disease diagnosis obtained from electronic health record to identify microbiome-health associations and to show how improved characterization of microbial diversity can provide new insights into microbiome-host interactions.

1. REVIEW OF THE LITERATURE

1.1 Microbiome: core concepts

The **microbiome** can be conceptualized as an ecosystem or a community, composed of numerous interacting microorganisms that collectively respond to internal feedback mechanisms and external perturbations (**Figure 1**).

In this context, the **metagenome** refers to the total genetic material recovered directly from a microbial community within a given sample (Handelsman et al. 1998).

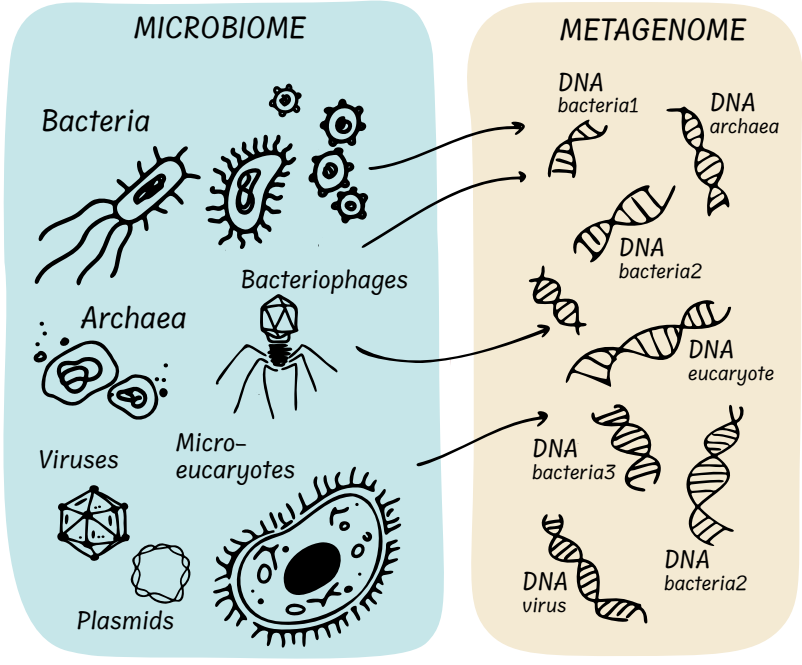

Figure 1. Microbiome and the metagenome as core concepts in microbiome studies. The microbiome represents the microbial community, while the metagenome represents its collective genetic content. Authors' own work.

The **human gut microbiome** refers to the community of microorganisms inhabiting the gastrointestinal tract. This community consists of hundreds of members and is dominated by bacteria, but also includes archaea, viruses, including bacteriophages, and microeukaryotes. Its composition and functional organization are influenced by a wide range of factors, including host genetics (Kurilshikov et al. 2021; Qin et al. 2022), age and geography (Yatsunenko et al. 2012), early-life exposures (Bolte, Moorshead, and Aagaard 2022), diet (Segev et al. 2026), medication use (Aasmets et al. 2022), and environmental factors (Rothschild et al. 2018). In addition to these external drivers, the gut microbiome is shaped by microbe-microbe interactions, host-microbe crosstalk, which together generate community-level properties that cannot be inferred from individual taxa alone.

Microbiome research focuses on communities of microorganisms, their interactions, and the collective properties that arise from these interactions. Microbiology provides the historical and conceptual foundation for microbiome research. A basic understanding of individual microbial components is necessary for studying complex communities, but it is not sufficient, as community-level behaviour is not equivalent to the sum of the behaviours of its individual members. As a result, microbiome research became feasible only when methodological advances enabled the assessment of entire microbial communities as integrated systems.

Genome-resolved metagenomics (GRM) is a metagenomic approach in which genomes of individual microorganisms are directly reconstructed from complex environmental or host-associated microbial DNA sequence data, without requiring cultivation (Kayani et al. 2021). By linking community-level sequencing data to reconstructed microbial genomes, GRM provides a framework for studying both taxonomic diversity and genome-level functional potential. GRM has become a major enabling technology for microbiome research (Pasolli et al. 2019) and now plays an important role in the emerging field of microbiome medicine (N. Kim et al. 2024; Ratiner et al. 2024).

1.2 Early stages of microbiome study

As the human gut microbiome is a complex system, it consists of many interacting components whose interactions are nonlinear, often adaptive. These interactions give rise to emergent, system-level behaviours that cannot be readily inferred from the properties of individual taxa alone. At the same time, a foundational understanding of the individual components and their basic functions remains essential.

Before the establishment of population-scale microbiome research, studies of human-associated microbial communities were largely framed as investigations of "microflora" or "microbiota" and were typically limited to small, specific sample sets. These studies relied mainly on cultivation, microscopy, FISH, targeted PCR, and Sanger sequencing of 16S rRNA genes, providing important early insights but only a partial view of microbial diversity (Tannock et al. 2000; Verhelst et al. 2005; Wilson and Blitchington 1996). A central limitation of these approaches was that many human-associated microorganisms are difficult, or even impossible, to cultivate under standard laboratory conditions. Suau et al. reported that microscopic counts suggested that 60–80% of observable fecal bacteria were not recovered by culture, while 16S rRNA clone libraries revealed numerous previously undescribed gut bacterial lineages (Suau et al. 1999). However, 16S rRNA-based profiling was also not a complete solution, as it relies on a single phylogenetic marker, has limited species- and strain-level resolution, and does not directly capture the functional gene content or metabolic potential of microbial communities.

These limitations motivated a shift toward high-throughput shotgun metagenomics, enabling standardized, population-scale analyses of both microbial community composition and functional potential (MetaHIT Consortium et al. 2010; Tonnelé et al. 2025). This shift was institutionalized through large international initiatives, most notably the NIH Human Microbiome Project (HMP), launched in 2007 (The Integrative HMP (iHMP) Research Network Consortium et al. 2019; The NIH HMP Working Group et al. 2009), and the European MetaHIT initiative (MetaHIT Consortium et al. 2010). These landmark initiatives leveraged advances in high-throughput sequencing to systematically catalogue microbial diversity across body sites and individuals, establishing the first comprehensive reference frameworks for the healthy human microbiome.

The HMP1 and HMP2 projects together generated more than 42 terabytes of publicly available data, including 16S rRNA gene profiles, whole-metagenome shotgun sequencing data and additional molecular measurements (The Integrative HMP (iHMP) Research Network Consortium et al. 2019; The NIH HMP Working Group et al. 2009). Early analyses based on 16S rRNA gene sequencing established a foundational view of microbiome composition across body sites, enabling the identification of broad ecological patterns such as pronounced inter-individual variability alongside site-specific community structures.

In parallel, the European MetaHIT project focused specifically on the human intestinal tract and placed whole-metagenome sequencing at the centre of its strategy. Rather than relying primarily on 16S rRNA gene surveys, its landmark study used Illumina shotgun sequencing of total DNA from faecal samples of 124 European individuals to reconstruct a catalogue of 3.3 million non-redundant microbial genes. This shift from taxonomic profiling towards gene-centred metagenomics was important because it allowed the gut microbiome to be described not only by which organisms were present, but also by the functional potential encoded by the community (MetaHIT Consortium et al. 2010).

Subsequent advances in shotgun metagenomics, especially *de novo* assembly and genome-resolved approaches, expanded reference collections and enabled recovery of metagenome-assembled genomes, thereby revealing previously uncultured and uncharacterized microbial diversity (Almeida et al. 2019).

Early large-scale studies revealed substantial inter-individual variability in taxonomic composition, whereas community functional profiles appeared comparatively more stable across individuals, a pattern also observed in the Estonian microbiome cohort (Aasmets et al. 2022). This apparent discrepancy has often been interpreted as evidence of functional redundancy, whereby different microbial taxa can perform similar ecological roles, thereby buffering taxonomic variation. However, an alternative explanation lies in methodological limitations: current functional annotations are strongly biased toward well-characterized, conserved genes that are widely shared across taxa. As a result, biologically meaningful variation may be obscured when analyses are restricted to broad pathway categories or to genes with established annotations, leaving a substantial fraction of functional diversity unresolved (Bradley and Pollard 2017).

1.3 Development of genome-resolved metagenomics

Metagenome assembly is the central component of genome-resolved metagenomics, as it enables reconstruction of individual microbial genomes directly from mixed-community shotgun sequence data, without the need for cultivation.

1.3.1 Main steps of metagenome assembly

The assembly workflow generally consists of several consecutive steps, from preprocessing of raw reads to genome reconstruction and quality assessment. After read quality control and removal of low-quality or host-derived sequences, short reads from one metagenomic sample are assembled into longer sequences, called **contigs**, based on sequence overlap.

Because these contigs originate from multiple community members, they are then grouped into **bins** using features such as sequence composition, including tetranucleotide frequency and GC content, differential coverage across samples, taxonomic marker genes, and, in some approaches, machine-learning-based classification. This process is called **binning.** To improve the quality of the final genome bins, multiple binning tools can be applied to the same metagenome sample, followed by comparison, refinement, and selection of the highest-quality bins. This strategy is often referred to as multi-binning.

Each bin is assessed for genome completeness and contamination, and, when it meets accepted quality criteria, reported as a **metagenome-assembled genome** (MAG). MAGs are subsequently assigned a taxonomic classification and functionally annotated (Chivian et al. 2023) (**Figure 2**).

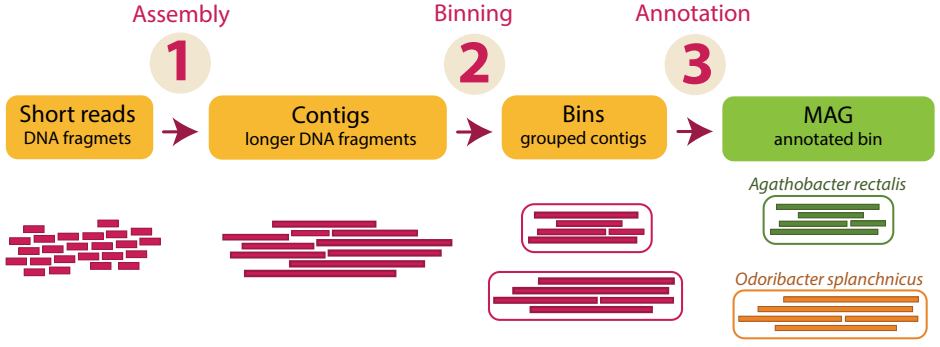

Figure 2. Schematic overview of metagenome assembly. In the first stage, short sequencing reads are assembled into longer DNA fragments called contigs based on sequence overlap. In the second stage, known as binning, contigs are grouped into bins based on their properties. In the final stage, each bin is evaluated for genome completeness, contamination, and taxonomic position. Bins with quality assessment and taxonomic classification are referred to as metagenome-assembled genomes (MAGs). Authors' own work.

MAG quality is commonly evaluated using two complementary metrics: genome **completeness** and genome **contamination**, both reported as percentages. In the original CheckM framework, these metrics were estimated using a lineage-aware approach based on curated sets of single-copy marker genes expected to be ubiquitous within the taxonomic lineage to which a MAG is assigned (Parks et al. 2015). Completeness is defined as the proportion of expected marker genes recovered in a MAG, whereas contamination is inferred from the occurrence of single-copy marker genes in multiple copies, which may indicate the sequences from other genomes (The Genome Standards Consortium et al. 2017) (**Figure 3**).

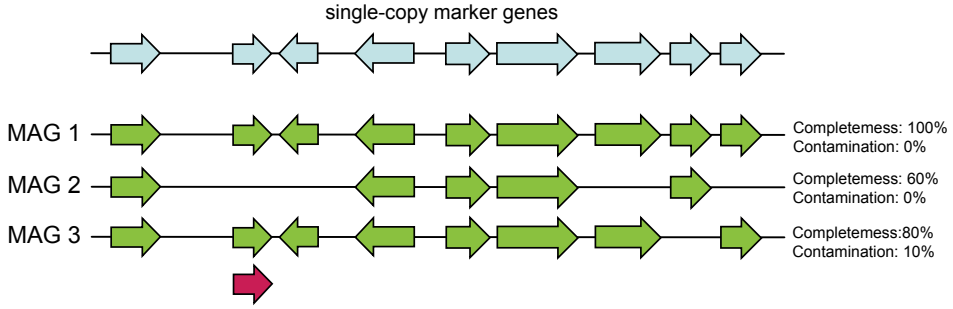

Figure 3. Schematic representation of completeness and contamination estimation. Lineage-aware, curated sets of single-copy marker genes expected to be present in a MAG are shown in blue. Marker genes recovered in the MAG are shown in green, whereas duplicated copies are shown in red. Completeness is defined as the proportion of expected marker genes recovered in the MAG, while contamination is inferred from the presence of single-copy marker genes in multiple copies. Authors' own work.

Although this approach performs well for well-characterized lineages, its accuracy can be reduced for poorly represented, highly divergent or reduced-genome lineages, where the expected marker-gene repertoire may differ from reference-based assumptions. To address these limitations, CheckM2 introduced machine-learning-based models for estimating MAG completeness and contamination, providing improved predictions across bacterial and archaeal lineages, including taxonomically new groups and reduced-genome taxa such as Patescibacteria and DPANN archaea (Chklovski et al. 2023).

According to the Minimum Information about a Metagenome-Assembled Genome (**MIMAG**) standard, MAG quality should be evaluated not only by estimated completeness and contamination, but also by assembly-related features, including the presence of rRNA and tRNA genes. Under this framework, high-quality draft MAGs are expected to be >90% complete and <5% contaminated, and to encode the 5S, 16S and 23S rRNA genes, together with tRNAs for at least 18 of the 20 standard amino acids. The same criteria were applied to single-amplified genomes (SAGs), i.e., genomes reconstructed from individual bacterial cells (**Table 1**) (The Genome Standards Consortium et al. 2017).

Table 1. MIMAG/MISAG genome quality categories and reporting standards for SAGs and MAGs

Genome category	Assembly quality	Complete-ness	Contami-nation	rRNA/tRNA requirements
Finished (SAG/MAG)	Single contiguous sequence without gaps or ambiguities with a consensus error rate equivalent to Q50 or better	~100%	0%	Complete rRNA and tRNA gene set expected.
High-quality draft (SAG/MAG)	Multiple fragments where gaps span repetitive regions.	>90%	<5%	Presence of the 23S, 16S, and at least 18tRNAs.
Medium-quality draft (SAG/MAG)	Many fragments with little to no review of assembly other than reporting of standard assembly statistics.	>50%	<10%	Not required
Low-quality draft (SAG/MAG)	Many fragments with little to no review of assembly other than reporting of standard assembly statistics.	<50%	<10%	Not required

SAG – single-amplified genome; MAG – metagenome-assembled genome; rRNA – ribosomal RNA; tRNA – transfer RNA.

However, rRNA and tRNA genes are often difficult to recover from metagenomic assemblies. These loci can occur in multiple copies and include highly conserved or repetitive regions, which are particularly challenging for short-read assembly. As a result, many MAGs with high estimated completeness and low contamination lack one or more rRNA or tRNA genes, despite otherwise satisfying the genomic completeness criteria. For MAGs with >90% completeness and <5% contamination that do not meet the full MIMAG rRNA/tRNA requirements, the term **near-complete MAGs** is often used (Almeida et al. 2019). Long-read and HiFi-based approaches can improve recovery of these difficult regions, including rRNA loci (C. Y. Kim, Ma, and Lee 2022).

The degree of genome fragmentation, reflected by the number of contigs, assembly gaps and contiguity statistics such as N50/L50, is also an important indicator of MAG quality. Although MIMAG recommends reporting assembly statistics, fragmentation is not defined as an explicit threshold for the main MAG quality categories and therefore should be considered as an additional quality descriptor rather than a primary classification criterion (The Genome Standards Consortium et al. 2017). This is particularly important when MAGs are used for accessory genome analysis or within-species comparisons, where fragmented assemblies may underestimate gene content or distort population structure.

1.3.2 History of metagenome assembly

Metagenome assembly has become a key approach for studying microbial communities in their natural environments and is still undergoing active development (**Figure 4**).The conceptual basis of this approach was formalised with the term *metagenome,* defined as the collective genetic content of a microbial community by Jo Handelsman and colleagues in 1998 (Handelsman et al. 1998). In its modern form, however, genome-resolved metagenomics was established by Gene Tyson et al. in 2004, who reconstructed near-complete genomes of *Leptospirillum* group II and *Ferroplasma* type II, along with partial genomes of three additional populations, from a low-complexity acid mine drainage biofilm (Tyson et al. 2004). This study provided the first clear demonstration that multiple genomes could be recovered directly from environmental samples, although at this stage the approach was mainly applicable to relatively simple communities dominated by a small number of populations with limited within-population diversity.

Subsequent work further clarified both the potential and limitations of metagenome assembly. In particular, Philip Hugenholtz and Gene Tyson highlighted key technical constraints, including the dependence on sequencing depth, community complexity, and accurate binning strategies (Hugenholtz and Tyson 2008). An important methodological advance followed in 2013, when Albertsen et al. applied differential coverage binning across multiple metagenomes to recover 31 bacterial genomes from activated sludge, including taxa with low relative abundance (Albertsen et al. 2013). This was a key step toward scalable metagenome assembly, because it showed that genome recovery was not limited to simple microbial system.

As the number of recovered MAGs increased, consistent quality assessment became essential. Tool such as CheckM a lineage-aware framework for estimating genome completeness and contamination and rapidly became a standard tool for evaluating draft genomes recovered from metagenomes (Parks et al. 2015). This was followed by the **MIMAG** and MISAG standard, which provided shared reporting guidelines for metagenome-assembled genomes (MAG) and single-amplified genomes (SAGs) and introduced a shared terminology for quality categories such as high- and medium-quality draft genomes (The Genome Standards Consortium et al. 2017). Together, these developments transformed metagenome assembly from a proof-of-concept approach into a reproducible framework for large-scale microbial genome recovery.

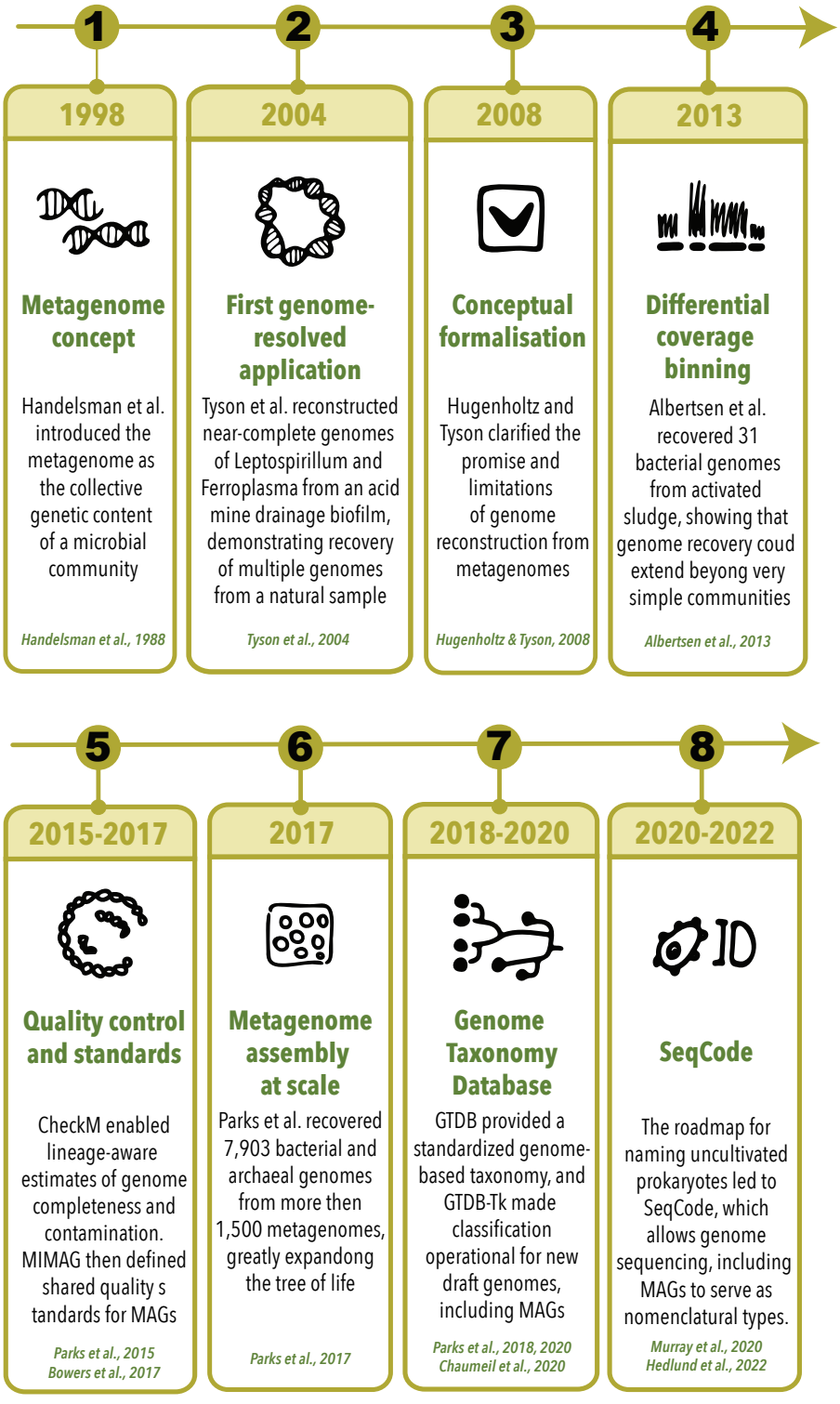

Figure 4. Timeline of major milestones in genome-resolved metagenomics. Authors' own work.

By 2017, the method had reached a new scale. Donovan Parks et al. reconstructed 7,903 bacterial and archaeal genomes from more than 1,500 public metagenomes, substantially expanding the known phylogenetic diversity and providing the first genomic representatives for many previously uncharacterized lineages (Parks et al. 2017). The rapid accumulation of genomes from uncultivated organisms created a strong demand for a standardized, genome-based taxonomic framework. This need was addressed by the Genome Taxonomy Database (GTDB), which applied phylogenomic principles to produce a rank-normalized taxonomy for Bacteria and Archaea (Parks et al. 2018, 2020). GTDB-Tk, a program for assigning GTDB taxonomy to new genomes, subsequently made this framework operational for newly recovered genomes, including MAGs, by enabling consistent taxonomic assignment of draft genomes (Chaumeil et al. 2020).

However, while GTDB provides a classification framework, it does not govern formal nomenclature. Under the traditional International Code of Nomenclature of Prokaryotes (ICNP), uncultivated organisms could not typically receive validly published names, as viable pure cultures were required as nomenclatural types. As the recovery of MAG and single-amplified genomes (SAG) recovery accelerated, this limitation became a major challenge for microbial systematics. A 2020 roadmap for naming uncultivated Archaea and Bacteria outlined the need for an alternative system, and the SeqCode later established such a system by allowing genome sequences themselves, including MAGs and SAGs, to serve as nomenclatural types (Hedlund et al. 2022; Murray et al. 2020; Whitman et al. 2022). In this sense, SeqCode can be viewed as the logical nomenclatural consequence of the metagenome assembly era.

1.4 MAG-based databases

The rapid expansion of genome-resolved metagenomics has driven the accumulation of vast numbers of microbial genomes and, in parallel, the emergence of large reference databases based on metagenome-assembled genomes (MAGs) (**Figure 5**). One of the key resources addressing this challenge is the GTDB, which provides a standardized genome-based taxonomic framework for bacteria and archaea (Parks et al. 2018, 2020). Building on this foundation, large-scale integrative resources have been developed to organize and explore microbial diversity across ecosystems.

GTDB provides a widely used genome-based framework for the taxonomic classification of bacteria and archaea, including both isolate genomes and metagenome-assembled genomes (Parks et al. 2018, 2020). By replacing primarily phenotype- and nomenclature-based assignments with a phylogenetically consistent, rank-normalized taxonomy, GTDB has become a central reference for interpreting prokaryotic diversity in genome-resolved microbiome studies. The most recent release, GTDB R232, issued on 15 April 2026, comprises 901,341 genomes in total, including 878,998 bacterial and 22,343 archaeal genomes. These genomes are organized into 199,923 species clusters, corresponding to 189,801 bacterial and 10,122 archaeal species clusters (Genome Taxonomy

Database. GTDB release R232. Genome Taxonomy Database. Available at: https://gtdb.ecogenomic.org/).

Among the broadest cross-habitat resources, **SPIRE** (Searchable, Planetary-scale mIcrobiome REsource) is currently one of the most comprehensive. SPIRE integrates data from a wide range of habitats, including human-associated, environmental, and engineered ecosystems, thereby substantially expanding known microbial diversity. As of May 2026, SPIRE integrates 99,067 metagenomic samples from 715 studies spanning diverse microbial environments and includes 1.16 million newly reconstructed medium- or high-quality MAGs, together with large-scale protein predictions and species-level genome clustering (Schmidt et al. 2024) (SPIRE. (2026). Searchable Planetary-scale mIcrobiome REsource. European Molecular Biology Laboratory. https://spire.embl.de). While GTDB focuses on standardized taxonomy, (Parks et al. 2022), SPIRE was developed as a searchable, integrative resource for comparative microbiome analysis across ecosystems. A major strength of SPIRE is its interoperability with companion resources. In particular, **VIRE** provides a planetary-scale catalogue of viral genomes reconstructed from a largely overlapping metagenomic universe, while **Metalog** supplies curated sample metadata and precomputed taxonomic profiles. Because these resources are linked through consistent sample identifiers, they enable joint exploration of microbial genomes, viral genomes, and associated contextual metadata from the same or overlapping samples (Kuhn et al. 2026; Nishijima et al. 2026). This interoperability substantially enhances the analytical value of SPIRE for ecological and multi-omic studies.

Such broad resources are valuable because they increase the representation of microbial genome space across environments. However, their broad scope also means that they may not always provide optimal resolution for a specific host population or cohort. While global resources such as the SPIRE database aim to capture microbial diversity across ecosystems, equally important efforts have focused on constructing high-resolution, habitat-specific reference databases.

For the human gut microbiome, the Unified Human Gastrointestinal Genome collection (**UHGG**) remains a foundational reference. Almeida et al. assembled a unified catalogue of nonredundant genomes representing 4,644 gut prokaryotic species and complemented it with the Unified Human Gastrointestinal Protein catalogue (UHGP), thereby consolidating previously fragmented isolate-based and MAG-based resources into a single framework (Almeida et al. 2021). By May 2026, UHGG v2.0.2 included 289,232 genomes representing 4,744 species-level clusters, comprising 4,716 bacterial species and 28 archaeal species (MGnify. (2024). Unified Human Gastrointestinal Genome (UHGG) v2.0.2. EMBL-EBI. Retrieved May 18, 2026, from https://www.ebi.ac.uk/metagenomics/genome-catalogues/human-gut-v2-0-2). This integration enables improved taxonomic resolution and functional annotation within the human gut microbiome. Importantly, more than 70% of the species in UHGG lacked cultured representatives, emphasizing the extent to which our current view of gut microbial diversity still depends on culture-independent genome recovery. Relative to GTDB, UHGG is habitat-specific rather than taxonomy-centred; relative to SPIRE, it exchanges environmental breadth for much deeper representation of a single, highly important host-associated ecosystem.

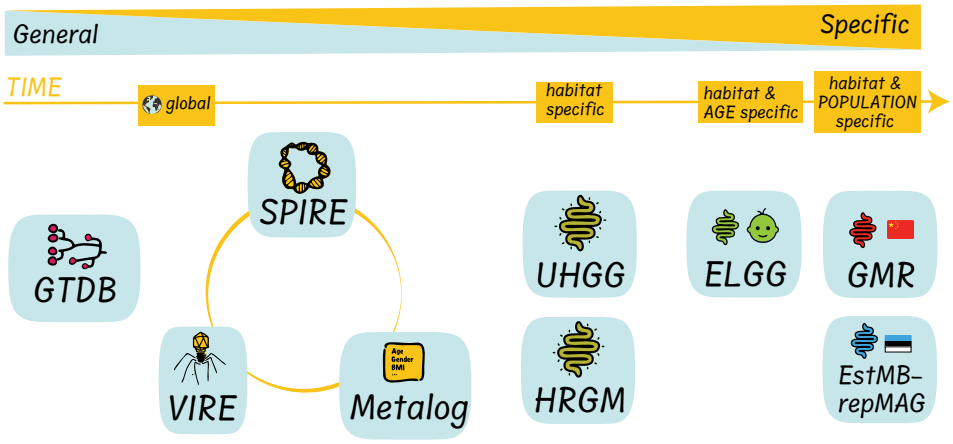

Figure 5. Overview of major MAG databases. Early resources aimed to capture microbial diversity at broad, global or cross-environment scales, as exemplified by the Genome Taxonomy Database (GTDB) and SPIRE, the Searchable Planetary-scale mIcrobiome REsource. More recent databases have increasingly adopted a targeted design, focusing on specific host-associated environments, such as the human gut in the Unified Human Gastrointestinal Genome (UHGG) and the Human Reference Gut Microbiome (HRGM), or combining environmental specificity with additional dimensions, including host age in the Early-Life Gut Genomes (ELGG) catalogue and population background in Gut Microbiome Reference (GMR) and Estonian Microbiome database (EstMB-repMAG). Authors' own work.

A closely related resource is **HRGM**, the Human Reference Gut Microbiome catalog. Kim et al. developed HRGM to address the geographic and population biases in earlier gut genome collections. By incorporating newly assembled genomes from underrepresented Asian metagenomes, HRGM expanded the available gut reference space to 232,098 nonredundant genomes representing 5,414 prokaryotic species, including 780 species do not present in prior catalogues (C. Y. Kim et al. 2021). Thus, the main contribution of HRGM is not simply numerical expansion beyond UHGG, but improved representation of human populations that had been under sampled in earlier resources.

HRGM2 extends this trajectory further by prioritizing genome quality and downstream functional interpretability. In this resource, Ma *et al*. compiled a catalog of near-complete genomes, defined as genomes with at least 90% completeness and no more than 5% contamination, derived from samples collected across 41 countries (Ma et al. 2025). Currently HRGM2 contains 155,211 nonredundant near-complete genomes from 4,824 prokaryotic species and was explicitly designed to improve functional profiling and genome-scale metabolic modelling. Although the total number of genomes is lower than in HRGM, this reflects a stricter quality threshold rather than a narrower biological scope.

Overall, the current trajectory of MAG database development is toward ever-broader genomic coverage, aiming to approximate the full spectrum of microbial species that may occur in a given habitat (Almeida et al. 2021; Schmidt et al.

2024). This approach is well justified, as reference-based profiling performs best when the database contains the genomes that are actually present in the sample. However, database expansion alone is not sufficient. As reference libraries become larger and more redundant, overlap among closely related genomes increases, which can reduce species-level precision by generating ambiguous or high-level taxonomic assignments and by increasing computational burden (Nyström-Persson, Bapatdhar, and Ghosh 2025).

For this reason, an equally important complementary strategy is the construction of population-, region-, or age-specific reference databases. Such resources can better capture lineage diversity underrepresented in broad global catalogues and improve taxonomic and functional profiling in the target cohorts. This is already evident in the human gut field: UHGG produced strong gains in read classification in understudied non-Western populations (Almeida et al. 2021), HRGM improved taxonomic and functional classification by incorporating genomes from underrepresented Asian cohorts (C. Y. Kim et al. 2021).

More recent MAG resources have moved beyond broad environment-specific catalogues by incorporating additional host- or population-level dimensions. For example, the Early-Life Gut Genomes (**ELGG**) catalogue provides an age-specific reference for the human gut microbiome during the first three years of life. ELGG comprises 32,277 MAGs representing 2,172 species reconstructed from 6,122 early-life faecal metagenomes, and increased recruitment of early-life metagenomic reads to 82.8%, supporting the value of life-stage-matched references for improving taxonomic and functional resolution (Zeng et al. 2022). Similarly, Dong et al. constructed the human Gut Microbiome Reference (**GMR**), a population-balanced gut genome resource comprising 478,588 high-quality microbial genomes from Chinese and non-Chinese populations. Their study showed that geographically imbalanced reference databases can underrepresent population-specific diversity: the authors reported that approximately 70% of existing microbial reference data derive from European and North American populations, while integration of new genomes into the taxonomic profiling database improved population-level species profiling by up to 23% (Dong et al. 2025).

In this context, our Estonian Microbiome Cohort-derived MAG resource (**EstMB-repMAG**) provides a further example of a targeted, environment- and population-specific reference, included 84,762 MAGs representing 2,257 species, including 353 previously uncharacterized species [**Ref. II**]. Such cohort-specific resources are not intended to replace global databases, but to complement them by improving detection of microbial diversity that is locally prevalent or underrepresented in broader catalogues.

Thus, the next phase of MAG database development should not be viewed simply as a race toward larger catalogues, but as a balance between breadth and contextual relevance.

1.4.1 Databases embedded in taxonomic profiling tools

It is important to distinguish general MAG-based genome catalogues from the databases embedded in taxonomic profiling tools. Profiling databases are usually transformed into algorithm-specific reference structures and are optimized for the classification strategy of a particular tool.

For example, **MetaPhlAn** uses clade-specific marker genes derived from reference genomes and MAGs from the human gut microbiome and also many other animal and ecological environments (Blanco-Míguez et al. 2023). Instead of operating directly with species as classical taxonomic units, it uses species-level genome bins (SGBs) as profiling units. Each SGB is a group of microbial genomes and MAGs cluster together on species-level. For each SGB, a specific set of marker genes is defined (average of 189 ± 34 unique marker genes per SGB), and species are detected through read mapping to a sufficient fraction of SGB-specific marker genes. The current MetaPhlAn4 database includes 26,970 high-quality species-level genome bins (SGBs).

mOTUs2 similarly relies on universal marker genes, combining reference-derived and metagenome-derived species-level units for microbial profiling, thereby enabling the profiling of more than 7700 microbial species (Milanese et al. 2019). **Kraken2** databases are built from taxonomically labelled genome sequences and represented as k-mers, with the option to use either standard or custom reference collections (Wood, Lu, and Langmead 2019).

These profilers are widely used as primary tools for taxonomic profiling, but their databases differ conceptually from MAG-based genome catalogues and are optimized for the underlying classification strategy, such as marker-gene detection or k-mer matching. As a result, they may provide limited flexibility for incorporating study-specific MAGs, with the exception of tools such as Kraken2 that explicitly support custom databases (Wood, Lu, and Langmead 2019). Moreover, marker-based profiling outputs are not always directly linked to complete genome sequences, which can limit follow-up analyses requiring genome-resolved functional annotation, comparative genomics, or strain-level investigation.

In this context, profiling directly against MAG-based catalogues, for example through read-mapping approaches such as **CoverM**, provides a complementary strategy in which reads are quantified directly against selected genome or MAG catalogues, including study-specific references (Aroney et al. 2025). This approach is particularly relevant when the aim is to quantify cohort-specific MAGs, newly reconstructed species, or within-species genome units.

1.5 Bacterial species concept and within-species diversity

Resources such as SPIRE, UHGG, and HRGM now contain hundreds or thousands of MAGs for many bacterial species. The accumulation of large numbers of genomes per species enables examination of within- species diversity at a scale that was previously impossible when analysis relied on a limited number of

cultured isolates. To understand the importance of within-species diversity, it is necessary to examine how the concept of species is defined in prokaryotes compared to eukaryotes.

In animals and plants, species are often defined using the biological **species concept**, which is based on sexual reproduction and reproductive isolation (Bozdag and Ono 2022; Westram et al. 2022). This framework does not transfer directly to bacteria, where reproduction is primarily clonal and genetic exchange is decoupled from reproduction itself (Bobay, Traverse, and Ochman 2015; Didelot et al. 2010). As a result, **bacterial species** are typically defined in terms of genomic cohesion rather than reproductive isolation (Fraser et al. 2009; Konstantinidis, Ramette, and Tiedje 2006; Rosselló-Mora 2001).

Genomic cohesion is commonly operationalized using whole-genome similarity measures, especially average nucleotide identity (ANI), which provides a quantitative estimate of nucleotide-level similarity between genomes (Goris et al. 2007; Konstantinidis and Tiedje 2005). Because ANI is a continuous variable, a key challenge is determining the threshold that separates genomes belonging to the same species from those that do not (Goris et al. 2007; Richter and Rosselló-Móra 2009). Large-scale analyses have shown that genomes assigned to the same species typically share at least about 95% ANI, whereas interspecies comparisons generally fall below this level, producing a clear discontinuity in genome similarity (Goris et al. 2007; Jain et al. 2018). This discontinuity underlies the widely used 95% ANI threshold for species delineation in prokaryotes (**Figure 6**). Thus, bacterial genomes sharing more than 95% ANI are generally considered to belong to the same species.

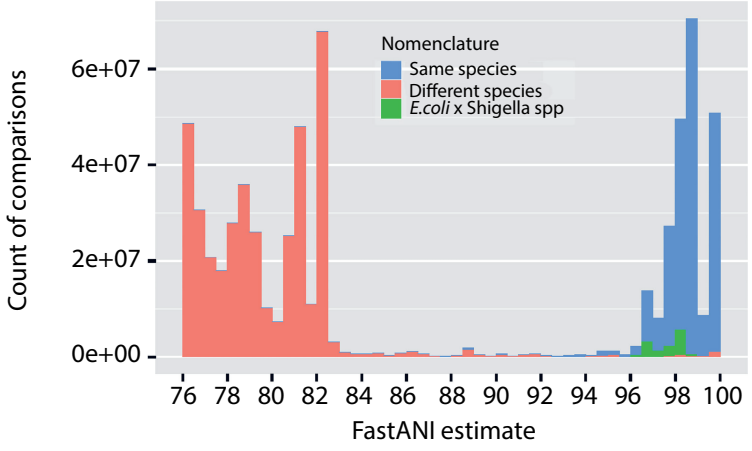

Figure 6. Distribution of average nucleotide identity (ANI) values for within- and between-species genome comparison. The figure shows the frequency distribution of pairwise ANI values across about 90,000 prokaryotic genomes. A clear discontinuity is observed around 95% ANI, separating within-species comparisons (high ANI values) from between-species comparisons (lower ANI values), which underlies the commonly used species boundary threshold (from Jain et.al.; 2018).

Although ANI provides a useful framework for species delineation, it captures nucleotide identity only across the orthologous fraction shared between genomes, rather than across their entire gene repertoire (Jain et al. 2018). This distinction is often described in terms of the core genome, which is shared by all members of a species, and the accessory genome, which varies between strains and may encode functions related to adaptation, metabolism or host interactions. Because homologous recombination, gene gain and loss, and horizontal gene transfer continuously reshape bacterial genomes, strains assigned to the same species on the basis of ANI may still differ extensively in accessory gene content (Diop et al. 2022; Rodriguez-R et al. 2024). As a result, genomes with highly similar core or shared-gene sequence identity can exhibit substantial differences in overall gene composition, highlighting that species assignment based on ANI does not imply functional uniformity (Rodriguez-R et al. 2024) (**Figure 7**).

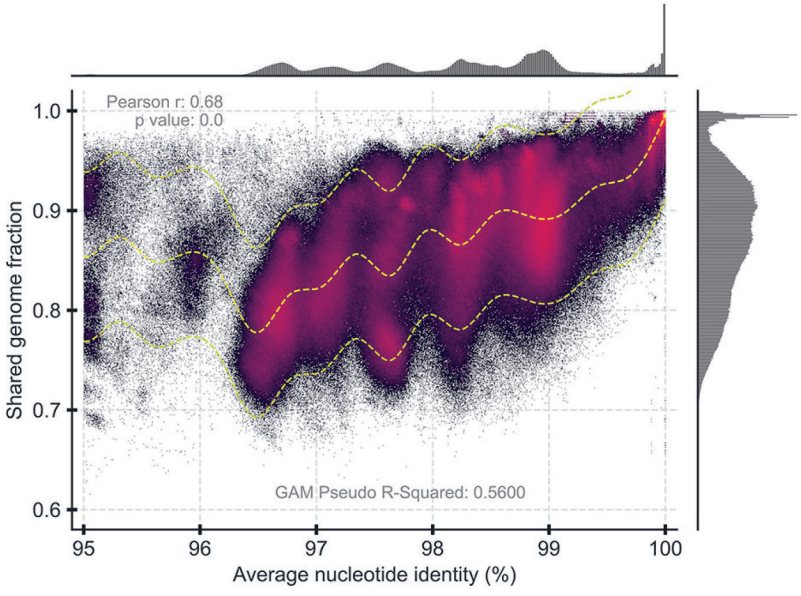

Figure 7. Relationship between averaged nucleotide identity (ANI) and shared genome fraction in prokaryotic genomes. The plot illustrates how genomes with similar ANI values can differ substantially in fraction of shared genes. Even at high ANI (>95%), a considerable variation in shared genome content is observed, reflecting differences in accessory genome composition (from Rodriguez et al.; 2024).

Consistent with these observations, a similar pattern is observed in the Estonian gut microbiome cohort. Among high-quality (HQ) MAGs assigned to the same species-level cluster, reconstructed genome length varies substantially. Across species represented by multiple HQ MAGs, the median normalized standard deviation of genome length is 0.11, reaching up to 0.43 in the most variable cases (**Figure 8**). This observation supports the need for finer-scale analysis beyond species-level classification. However, genome-length variation in MAG should be interpreted cautiously, because it may reflect both biological differences in accessory genome content and technical factors such as incomplete assembly, fragmentation, or binning uncertainty.

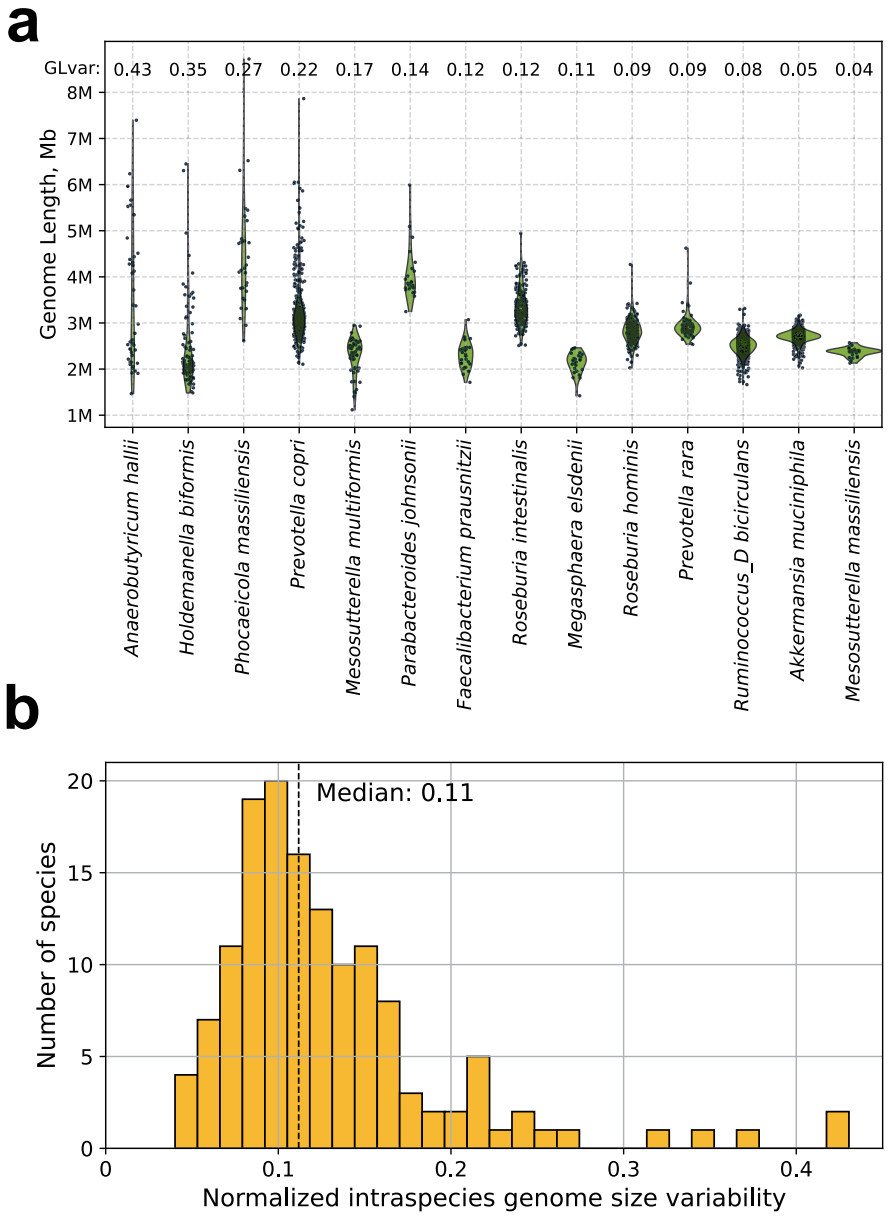

Figure 8. Within-species variation in reconstructed genome length among gut bacterial species in the Estonian microbiome cohort (N=2504 individuals) **a.** Genome length distributions for the most variable and least variable species, illustrating the extent of within-species genomic diversity. These results demonstrate that substantial genome length variation exists within species-level clusters, supporting the need for finer-scale resolution beyond species-level classification. Each dot represents one genome, and the numbers above the plots indicate genome size variability for each species. **b.** Distribution of normalized genome-length variation across species-level clusters represented by more than 100 high-quality (HQ) MAGs. *(not published)*

1.6 Future perspectives

Observations about between-species and within-species differences, we discussed in previous chapter, indicate that bacterial species often function as umbrella categories that encompass multiple genetically and ecologically distinct populations, rather than uniformly cohesive biological entities (Conrad et al. 2024; Viver et al. 2024). For studies aimed at linking the microbiome to host phenotype, species-level of resolution may therefore be insufficient, as substantial within-species genomic variation can translate into differences in microbial function and distinct associations with host traits (Zeevi et al. 2019; Zhernakova et al. 2024).

In this context, it is necessary to move beyond species-level classification and consider finer-scale units. Although these units are often referred to as **strains**, the term strain is traditionally reserved for descendants of a single cultured isolate and is best applied to nearly identical genomes (Van Rossum et al. 2020; Viver et al. 2024). For association analyses, a more suitable framework is to define stable within-species populations with coherent genomic content and, ideally, coherent functional potential, rather than relying solely on species-level classifications.

1.6.1 Within-species population structure

As discussed in the previous chapter, the genome-based concept of prokaryotic species has only recently become established (Jain et al. 2018; Parks et al. 2022). However, defining species boundaries is only the first step. The rapid accumulation of thousands of genomes per species has revealed that the diversity contained within a single named species is often much greater than previously appreciated. Bacterial species, once commonly treated as largely clonal populations (Smith et al. 1993), are now increasingly understood as umbrella categories encompassing multiple genetically and ecologically distinct populations.

This realization opens an important direction for future research: moving beyond species-level comparisons toward a detailed understanding of **within-species structure**. Under current operational definitions, genomes assigned to the same species may differ by up to 5% in shared genome sequence similarity, while differences in accessory gene content can be substantially larger (Conrad et al. 2024; Rodriguez-R et al. 2024). Such variation may reflect differences in ecological niches, host adaptation, recombination dynamics, mobile genetic elements, metabolic capabilities, virulence, or antimicrobial resistance.

A key challenge is to determine which within-species differences represent stable biological populations and which reflect technical artefacts introduced by sequencing depth, fragmentation, binning errors, or database incompleteness. This distinction is especially important when within-species units are used in downstream association analysis.

1.6.2 Technical limitations of metagenome sequencing

To achieve the detailed understanding of within-species structure described above, it will be critical to obtain high-quality genomes representing all major genomic units within each species. In addition, sufficiently large numbers of genomes are required to capture the complete repertoire of accessory genes and to enable statistically robust analyses.

A major technical limitation is that current short-read-based metagenomic assembly approaches remain insufficient for this task. Although metagenome-assembled genomes have greatly expanded the known diversity of uncultivated microorganisms (Nayfach et al. 2021; Parks et al. 2017), their quality is often limited by incomplete assembly, contamination, fragmented genomes, and the formation of composite MAGs when several closely related strains co-occur in the same sample (Chen et al. 2020; Shaiber and Eren 2019).

Genome quality can be improved by selecting only high-quality MAGs based on tools such as CheckM (Parks et al. 2015; The Genome Standards Consortium et al. 2017) and by applying additional quality-control approaches such as GUNC to detect chimerism or taxonomic inconsistency (Orakov et al. 2021). However, these improvements are unlikely to fully resolve the problem. Even high-quality short-read MAGs may fail to capture plasmids, phages, repetitive regions, strain-specific islands, and other accessory elements that are essential for understanding within-species diversity (Bertrand et al. 2019; Moss, Maghini, and Bhatt 2020; Suzuki et al. 2019). Therefore, additional methodological advances will be required.

One promising direction is the increased use of long-read sequencing, which can produce more contiguous assemblies and improve the recovery of complete chromosomes, plasmids, and mobile genetic elements (Bertrand et al. 2019, 2019; Moss, Maghini, and Bhatt 2020). Complementary methods such as Hi-C sequencing can further improve genome reconstruction by linking contigs to the same genome and enhancing binning accuracy (Bickhart et al. 2022; DeMaere and Darling 2019). Hybrid strategies that integrate short reads, long reads, and proximity ligation data are particularly promising for resolving complex microbial communities in which multiple closely related strains coexist (Bertrand et al. 2019; Bickhart et al. 2022).

However, the large-scale application of these approaches in population-based studies remains limited by cost, throughput, and computational demands. A complementary and highly reliable approach is to combine metagenomic analysis with systematic cultivation (Lewis et al. 2021). Where possible, representative isolates could be obtained for major genomic units within a species, followed by high-quality sequencing and complete genome assembly. Such isolate genomes would provide robust references for interpreting MAGs, defining accessory-gene repertoires, resolving within-species population structure, and validating species-specific genomic units. However, many microbial taxa remain difficult to culture, limiting the scalability of this approach. Therefore, cultivation-based strategies will need to be integrated with genome-resolved metagenomics and emerging technologies such as long-read and single-cell sequencing.

2. AIMS OF THE STUDY

This thesis investigates the potential of genome-resolved metagenomics as a framework for studying human microbiome communities and their associations with human health. It first evaluates the comparability of metagenomic profiles generated on two short-read sequencing platforms, which is essential for integrating data across large population-based cohorts. The thesis then focus on the large-scale reconstruction of metagenome-assembled genomes (MAGs) from a population-based cohort, the development of a population- specific MAG reference database, and downstream association analysis. In addition, the thesis introduces a framework for detecting microbiome-health associations at the within-species level.

The specific aims of the thesis are as follows:

- To systematically compare matched human stool metagenomes generated on two short-read sequencing platforms and assess platform-related effects on taxonomic and functional profiling, in order to evaluate the feasibility of integrating data across large population-based cohorts.
- To reconstruct metagenome-assembled genomes (MAGs) from the Estonian Microbiome deep (EstMB-deep) cohort, capturing both bacterial and archaeal diversity, and to establish a population-specific MAG reference database.
- To perform species-level association analyses and develop a framework for within-species-level association studies in large population-based cohorts.

3. MATERIAL AND METHODS

The human gut microbiome samples analysed in this thesis, together with the experimental procedures and analytical workflows, are described in detail in the corresponding original publications and their supporting materials. Here, I provide a brief overview of the study design, datasets and main methodological approaches used in the three studies included in this thesis.

The DNA samples were obtained from unrelated volunteers from Estonian biobank who provided informed consent. Sample collection and data generation were conducted in accordance with the guidelines and approval of the relevant ethics committees.

All three studies included in this thesis were based on the Estonian Microbiome Cohort (EstMB), a population-based cohort of 2,409 adult volunteers from the Estonian Biobank. The cohort includes stool metagenomic sequencing data together with host metadata, and linkage to national electronic health records (EHRs) enables microbiome–health association analyses. In this thesis, EstMB was used in two complementary forms: a broader moderately sequenced dataset for microbiome profiling and association analyses, and a deeply sequenced subset, referred to as EstMB-deep, for metagenome assembly and MAG reconstruction.

An overview of the datasets, sample sizes, methodological approaches, and main outputs of the studies included in this thesis in Table 2.

Table 2. Overview of the datasets and main outputs of the studies included in this thesis

Study	Dataset	Number of samples	Main output
Ref I	matched human stool metagenomes	1,351 samples	Assessment of sequencig platform concordance and platform related effects
Ref II	EstMB-deep and full EstMB cohort	1,878 deeply sequenced samples for MAG reconstrution; 2,504 moderately sequenced samples for downstream profiling and association analysis	EstMB-repMAG population-specific reference database, microbiome-health associations
Ref III	Archaeal MAGs from EstMB-deep	1,878 deeply sequenced samples	Human gut archaeal MAG collection and incorporation into the population-specific reference database

In the first study, paired metagenomic sequencing data generated on two independent sequencing platforms, MGISEQ-2000 and NovaSeq 6000, were compared. The dataset included 1,729 individuals from the Estonian Microbiome Cohort (EstMB), each with a sample sequenced on both platforms. A subset of 53 individuals was additionally sequenced twice on the same platform, allowing the assessment of within-platform technical variability. This study design enabled a systematic comparison of cross-platform and within-platform variability in taxonomic and functional microbiome profiles (**Ref. I**).

In the second study, we used 1,878 deeply sequenced samples from the Estonian Microbiome Cohort, hereafter referred to as EstMB-deep, were used for metagenome reconstruction. Metagenome-assembled genomes (MAGs) reconstructed from these samples were used to generate a cohort-specific reference database for subsequent microbiome profiling. Because these profiles served as the basis for downstream association analyses, maximizing the number of profiled samples was an important consideration. Therefore, the cohort-specific reference database was applied to moderately sequenced samples from the broader EstMB cohort, comprising 2,504 samples, thereby increasing the sample size available for microbiome-health association analysis (**Ref. II**).

In the third study, metagenomic data from the EstMB-deep cohort were re-analysed to specifically reconstruct archaeal metagenome-assembled genomes. For this purpose, the MAG catalogue generated in the second study was revised, with particular attention to genomes that had been excluded during the dereplication step. This strategy was used because excluded genome bins could contain archaeal MAGs that were not retained in the final bacterial MAG database. Targeted curation enabled the recovery of archaeal MAGs, including genomes representing potentially new archeal species. These genomes were subsequently incorporated into the population-specific reference database (**Ref. III**).

4. RESULTS AND DISCUSSION

4.1 Microbiome community profiling (Ref. I)

Microbiome community profiling defines the taxonomic composition of a given microbiome and in sequencing-based studies, typically estimates the relative abundance of the microorganisms present. This information provides the foundation for most downstream microbiome analyses.

The standard output of community profiling is an **abundance table**. In this table, rows usually represent taxa, such as species, genera or strains, and columns represent samples (**Figure 9**). Each value indicates the relative abundance of a given taxon in each sample. Absolute abundance is less commonly available because it requires additional information on the total microbial load in each sample (Morton et al. 2019). This can be estimated using approaches such as flow cytometry (Vandeputte et al. 2017). quantitative PCR (Galazzo et al. 2020) or spike-in standards (Barlow, Bogatyrev, and Ismagilov 2020), but these methods require extra laboratory procedures and increase cost.

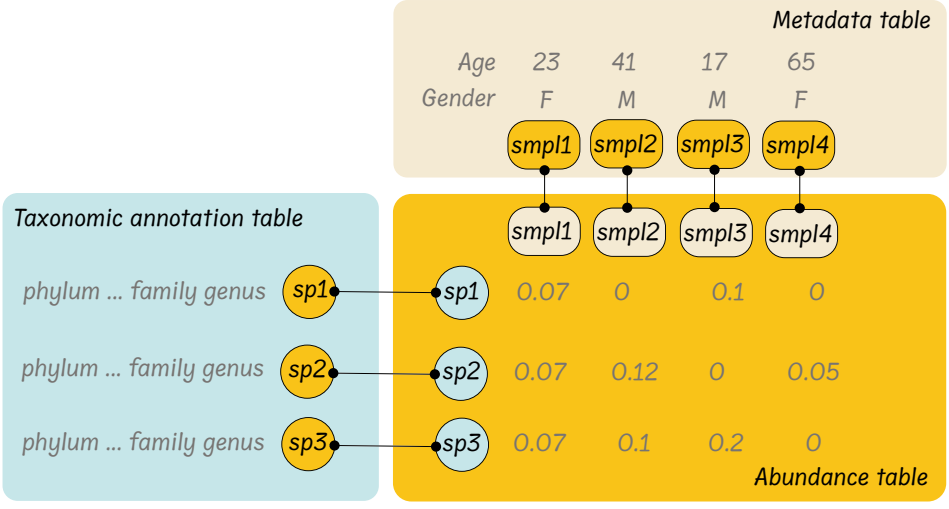

Figure 9. Core input tables for microbiome analysis and their interconnections. The abundance table is accompanied by a taxonomic annotation table, linked through species identifiers, and a metadata table, linked through sample identifiers. Smpl, samples, sp-species. Authors' own work.

Abundance tables are typically accompanied by a **taxonomic annotation table**. This table provides the full taxonomic classification of each feature detected in the abundance table, from higher taxonomic ranks to species or strain level when available. The abundance and taxonomy tables are linked through shared taxon or feature identifiers.

Community profiling data are often further complemented by sample **metadata table**. Metadata describe relevant characteristics of each sample or individual, such as age, sex, body mass index, stool type, disease status, treatment group or other clinical and environmental variables. These metadata are linked to the abundance table through sample identifiers.

Abundance table generation

The abundance tables, accompanied with taxonomic annotation table, serve as a central intermediate for a wide range of downstream analyses, including diversity estimation, microbiome-disease association studies, and functional inference. Despite its critical role, the influence of upstream methodological choices on the resulting abundance estimates remains underappreciated, and analytical attention is frequently directed toward subsequent steps rather than the nuances of the profiling process itself. Differences between DNA extraction protocols, sequencing platforms, profiling tools and profiling databases may introduce systematic biases that affect the reproducibility and comparability of microbiome studies (**Figure 10**).

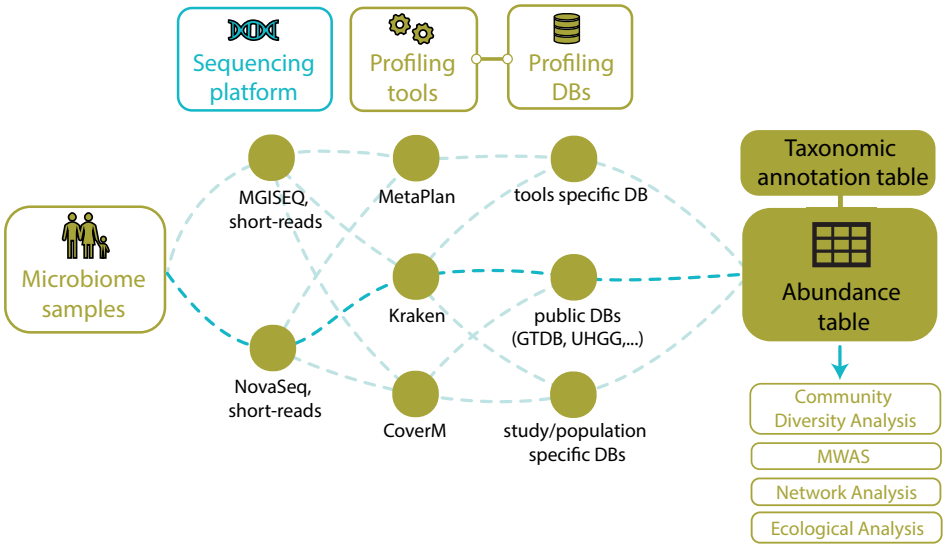

Figure 10. Schematic overview of abundance table generation as a central intermediate step in microbiome analysis workflows. The choice of sequencing platform, taxonomic profiling tool, and profiling database can influence the resulting abundance table and, consequently, all downstream analyses, interpretations, and biological conclusions. Sequencing platforms are highlighted in blue, as that factor is discussed in this chapter. Authors' own work.

In our first study, we aimed to address this gap and performed a large-scale comparative metagenomic analysis of short-read sequencing platforms, including taxonomic concordance and functional analysis.

4.1.1 Taxonomic concordance among sequencing platforms

To evaluate whether abundance tables produced from different sequencing platforms are comparable and suitable for combined downstream analyses, we analysed matched human stool metagenomes generated from the same DNA extracts. Because all samples were profiled using the same bioinformatic pipeline and reference databases, any observed differences in taxonomic abundance profiles could be attributed primarily to the sequencing platform rather than to differences in taxonomic annotation or computational processing.

The analysis included matched human stool metagenome samples from the Estonian Microbiome cohort. In total,1,351 sample paris passed the filtering criteria used for this comparison. Each pair originated from a different individual and was sequenced twice: once on the NovaSeq 6000 platform, hereafter NovaSeq, and once on the MGISEQ-2000 platform from MGI Tech Co., Ltd., hereafter MGI.

Before evaluating **cross-platform** variability, we first estimated the expected background variability introduced by sequencing and taxonomic profiling alone. For this purpose, we analysed an additional set of 53 technical replicate sample pairs generated on the same sequencing platform. This **intra-platform** comparison provided a baseline for the variability observed when the same sample is sequenced and processed under comparable platform conditions. Thus, the central question was not simply whether taxonomic profiles differed between NovaSeq and MGI, but whether the variability between platforms exceeded the background variability observed within a single platform.

The percentage of run-specific species was 3.42% in the intra-platform comparison, corresponding to 37 out of 1,083 detected species. In the cross-platform comparison, this percentage was slightly higher, at 5.89%, corresponding to 174 out of 2,953 detected species. However, the total number of detected species was nearly three times higher in the cross-platform dataset, likely reflecting the substantially larger number of sample pairs included in this comparison: 1,351 cross-platform pairs compared with 53 intra-platform technical replicate pairs. Therefore, the higher number of set-specific species in the cross-platform comparison should be interpreted with caution and may partly reflect the larger sample size rather than a sequencing platform effect alone.

Most platform-specific taxa were rare. Of the 174 species detected only in one platform, 154 were present in only a single sample. Their mean relative abundance was also markedly lower than that of shared species, at 1.30×10^{-6} % compared with 2.85×10^{-4} %, respectively. These results indicate that most platform-specific detections were unlikely to represent major differences in community composition, but rather reflected rare, low-abundance taxa close to the detection limit.

The difference in the number of detected species per sample pair was statistically significant in both the intra-platform comparison (P value = 0.038) and the cross-platform comparison (P value = 1.03×10^{-7}). However, the effect sizes were small in both cases, with Cohen's d = 0.29 for the intra-platform

comparison and Cohen's d = −0.12 for the cross-platform comparison. The negative sign of Cohen's reflects the direction of the platform differences rather than a larger effect. Therefore, despite statistical significance, the magnitude of the differences was limited.

We then performed sample-matched comparisons to assess concordance at the individual sample level. These analyses included the percentage of shared species within sample pairs, the correlation of species prevalence and relative abundance between sequencing runs, and the difference in Shannon diversity index between matched sample pairs, assessed using a paired t-test. The mean percentage of shared species within sample pairs was 96.44% ± 5.96% in the intra-platform comparison and was slightly lower in the cross-platform comparison, at 92.07% ± 5.20% (**Figure 11a, b**).

Species prevalence and relative abundance showed strong agreement between sequencing runs, with R^2 values approaching 1.0 in both the intra-platform and cross-platform comparisons (**Figure 11c–f**). Similarly, no significant difference in Shannon diversity was observed between paired profiles in either comparison (paired t-test, P value > 0.05).

Overall, these results show that taxonomic abundance tables generated from different sequencing platforms exhibit some set-level differences, including differences in the total number of detected species and the presence of platform-specific taxa. However, these differences were only modestly higher than the variability observed within a single platform, and most platform-specific taxa were rare and low in abundance. Cross-platform profiles remained highly concordant, with a high proportion of shared species and strong agreement in species prevalence, relative abundance, and diversity estimates. Together, these findings indicate that taxonomic abundance tables generated from NovaSeq and MGI sequencing data are broadly comparable and can be considered suitable for combined downstream taxonomic analyses when processed using the same taxonomic profiling pipeline and reference database. Nevertheless, comparisons involving rare or very low-abundance taxa should be interpreted with caution, as these taxa are most sensitive to platform-specific detection differences.

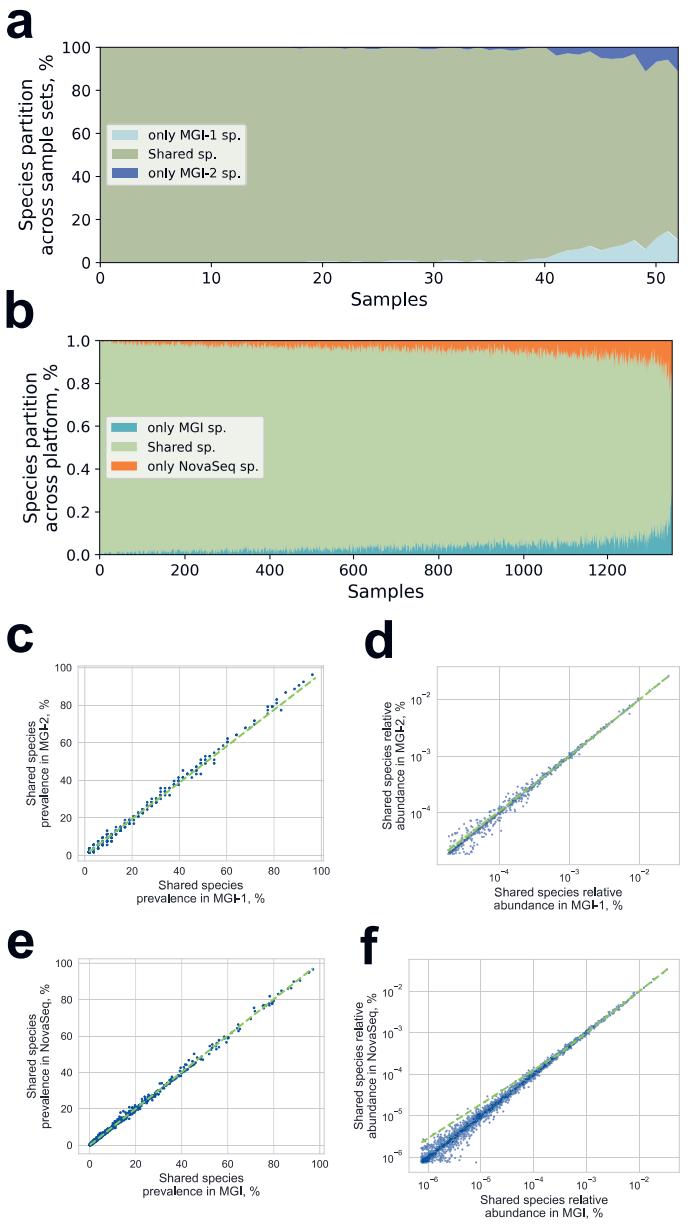

Figure 11. Taxonomic composition comparison within sequencing platforms and between sequencing platforms. **a.** The percentage of shared and unique run-specific species within each sample pair for the intra-platform baseline comparison. **b.** The percentage of shared and unique run-specific species within each sample pair for the cross-platform comparison. **c.** Comparison of the prevalence of shared species between matched samples, intra-platform baseline comparison. **d.** Comparison of the relative abundance of shared species in matched samples, intra-platform baseline comparison. **e.** Comparison of the prevalence of shared species between matched samples, cross-platform comparison. **f.** Comparison of the relative abundance of shared species in matched samples, cross-platform comparison.

4.1.2 Functional analysis challenges

Metagenomic sequencing enables both taxonomic and functional profiling of microbial communities, allowing researchers to characterize not only which microorganisms are present in a sample, but also their potential functional capabilities based on gene and pathway composition.

To assess platform-specific effects on functional profiling, we compared a random subset of 700 matched sample pairs sequenced with MGI and NovaSeq. Functional annotation identified 1,170 unique enzymes, of which only 31 were platform-specific, indicating broad agreement between technologies at the level of enzyme detection.

Nevertheless, MGI consistently recovered a higher number of enzymes and greater pathway recall, particularly in sample pairs with lower functional overlap. These differences were not restricted to rare functions, but also affected common enzymes involved in central metabolic pathways, suggesting a systematic shift in functional representation. K-mer analysis further showed that MGI samples contained substantially greater sequence diversity (**Figure 12a**), while the number of taxonomically assigned reads remained comparable between platforms. In contrast, MGI produced markedly more functionally annotated reads, indicating that higher sequence diversity had a stronger effect on functional annotation than on taxonomic profiling (**Figure 12b**). Functional differences were not explained by taxonomic variation, as taxonomic and functional similarity were not correlated, and coverage analysis revealed platform-specific differences across genomic regions.

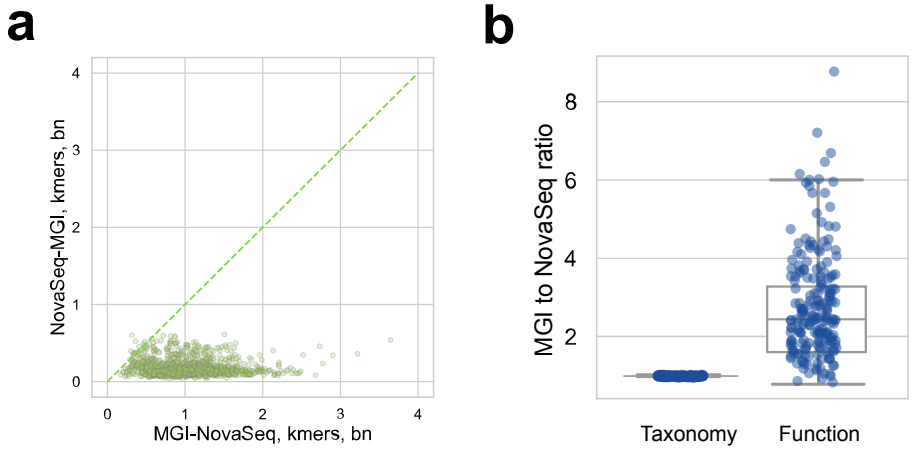

Figure 12. Platform-specific sequence and annotation differences. **a.** Unique k-mers per sample: in NovaSeq versus MGI and vice versa. **b.** Contributions of taxonomic and functional microbiome components found uniquely in MGI or NovaSeq.

Together, these results indicate that MGI data contained more sequence diversity, which was associated with improved functional annotation more than with changes on taxonomic annotation. More broadly, these findings show that functional profiling is more sensitive than taxonomic profiling to sequencing -platform-related differences, including read depth, sequence complexity, and uneven genome coverage. However, these results should not be interpreted as evidence that one sequencing platform is inherently superior for functional profiling. Rather, they support the broader view that a substantial part of the microbiome's functional "dark matter" reflects limitations in library complexity and functional reference catalogues, not simply differences between sequencing platforms (Treichel et al. 2026). Therefore, improving functional metagenomics requires not only platform comparison, but also optimized library preparation, adequate unique coverage, and improved functional gene catalogues. Consequently, although taxonomic profiles generated on MGI and NovaSeq were highly concordant, functional profiles should be interpreted with greater caution when data from different sequencing platforms are combined.

4.2 Genome-resolved metagenomics (GRM) (Ref. II, Ref. III)

Genome-resolved metagenomics has transformed our ability to characterize microbial communities by revealing multiple layers of diversity that remain hidden to classical profiling approaches.

First, it enables the reconstruction of previously **uncharacterized species** directly from metagenomic data, thereby recovering new taxa that would otherwise remain entirely undetected. Second, when applied across large cohorts, genome reconstruction yields multiple genomes per species, enabling investigation of **within-species variation** and its links to functional potential and ecological roles. Third, even within a single sample, microbial populations often consist of closely related co-existing strains. Such **within-sample within-species** variation is typically unresolved by both profiling methods and standard short-read GRM approaches and therefore requires more advanced strategies.

Here, we describe the assembly strategy applied to our cohort and assess its performance in capturing these three layers of previously hidden microbial diversity.

4.2.1 Metagenome reconstruction

MAG reconstruction across the EstMB-deep cohort was based on per-sample assembly with MEGAHIT, followed by consensus binning with MetaBAT v2.15, MaxBin v2.2.7, and VAMB v3.0.7, with bin selection performed by DAS Tool v1.1.4. This strategy was chosen to enable efficient processing of numerous high-coverage samples while maximizing MAG recovery robustness across diverse microbial genomes. Overall, **84,257 MAGs** were recovered, of which

42,224 were classified as near-complete MAGs (completeness >90% and contamination <5%, as assessed by CheckM2).

Species-level clustering with dRep further resolved these genomes into **2,257 species clusters**, each represented by the highest-quality MAG together with additional MAGs assigned to the same species that passed the standard inclusion thresholds applied for dereplication, completeness >50% and contamination <25% (**Figure 13**).

Because no **archaeal** genomes were retained among the final species representative MAGs, we performed an additional screening of MAGs excluded during the dereplication step to assess archaeal representation within the broader MAG collection. Taxonomic annotation of the 27,284 excluded MAGs using GTDB-Tk (release 214) identified 316 candidate archaeal MAGs.

These genomes were subsequently evaluated using CheckM for genome quality assessment, SeqKit for genome size estimation, and contig-level annotation with GUNC to verify taxonomic consistency. MAGs with low quality (completeness <50% or contamination >10%), abnormal genome size (>2 Mb), or inconsistent contig-level annotation (<50% of contigs assigned to the same archaeal taxon) were excluded, yielding a final set of 273 archaeal MAGs. Species-level clustering of these archaeal genomes further resolved them into 21 species clusters.

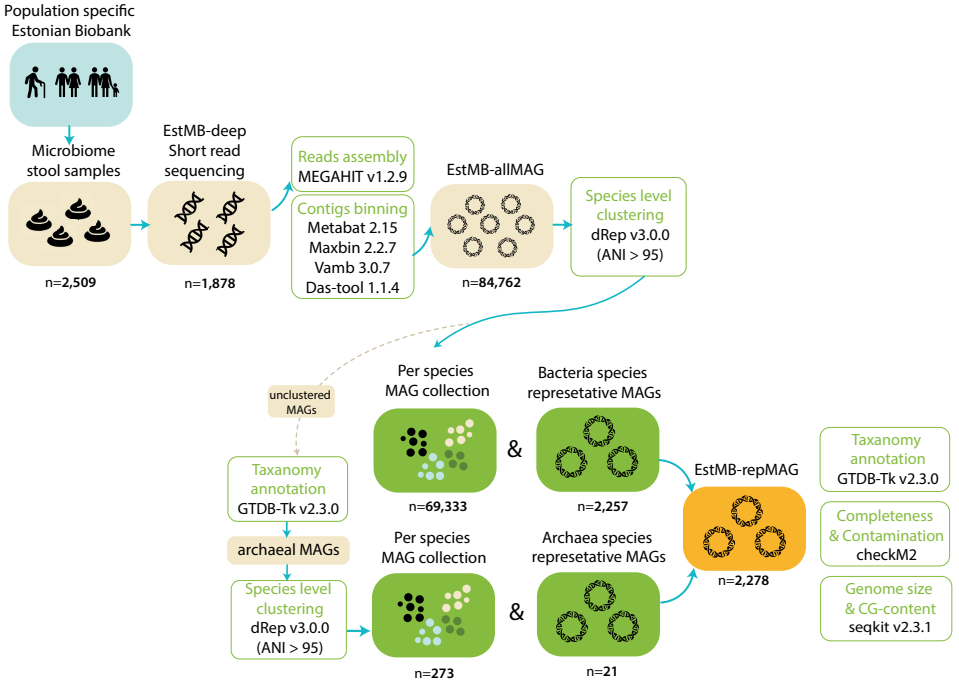

Figure 13. Overview of the MAG reconstruction and species-level clustering workflow applied to the EstMB-deep cohort.

In total, the final representative genome collection from the Estonian population comprised 2,257 bacterial and 21 archaeal species-representative MAGs. This final representative genome catalogue is hereafter referred to as **EstMB-repMAG**.

To ensure consistency across EstMB-repMAG, all MAGs were uniformly annotated using GTDB-Tk, genome statistics were estimated with SeqKit, and genome quality was assessed using CheckM2 (**Figure 13**).

4.2.2 Hidden diversity of a new species

One of the key advantages of genome-resolved metagenomics is the ability to recover previously uncharacterized microbial species directly from sequencing data, thereby expanding microbial diversity beyond the limits of existing reference databases. Unlike reference-based approaches, de novo genome reconstruction can recover both known and previously uncharacterized taxa, making it particularly valuable for identifying population-specific microbial diversity that remains absent from current catalogues.

New species discovery

To evaluate the extent of previously uncharacterized microbial diversity recovered from the EstMB cohort, reconstructed MAG species clusters were compared against the GTDB reference database. We quantified the proportion of new species among all reconstructed species clusters. Among bacteria, 353 species were classified as new, corresponding to 15.6% of all recovered bacterial species clusters. Among archaea, 10 of 21 species clusters (47.6%) were classified as new at the time of assembly (**Figure 14a,b**).

Given that the latest release of the UHGG database contains approximately 4,600 bacterial species and 27 archaeal species, the number of newly identified taxa indicates that substantial unexplored diversity remains even within the human gut microbiome, particularly among archaea, which remain underrepresented in current reference catalogues (**Ref. III**).

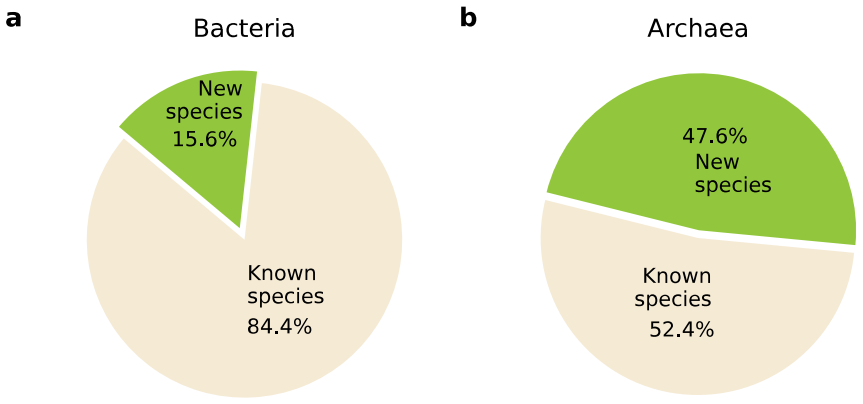

Figure 14. Overview of new species identified from the EstMB MAG collection. **a.** Proportion of new bacterial species among all reconstructed species clusters. **b.** Proportion of new archaeal species among all reconstructed species clusters.

Archaea diversity in Estonian population

Given the complexity of metagenome assembly, we anticipated that not all species present in the population would have corresponding MAGs. To gain a more comprehensive understanding of archaeal diversity in our population, we supplemented our species-level representative MAG collection "Archaea ESTrep-21" (n=21) with publicly available archaeal MAGs and genomes from the UHGG collections v2.0.2 (n=28) (Almeida et al. 2019). We performed species-level dereplication for 21 species from the 'Archaea ESTrep-21' collection and 28 species from the UHGG collection. Following this process, we compiled a refined set of 37 unique species, which we refer to as **'Archaea GUTrep-37'** (**Figure 15a**). Of these, 12 species were shared between the "ESTrep-21" MAG collection and the UHGG collection, while 16 species were exclusive to the UHGG collection, and 9 species were unique to the "ESTrep-21" MAG collection (**Figure 15b**).

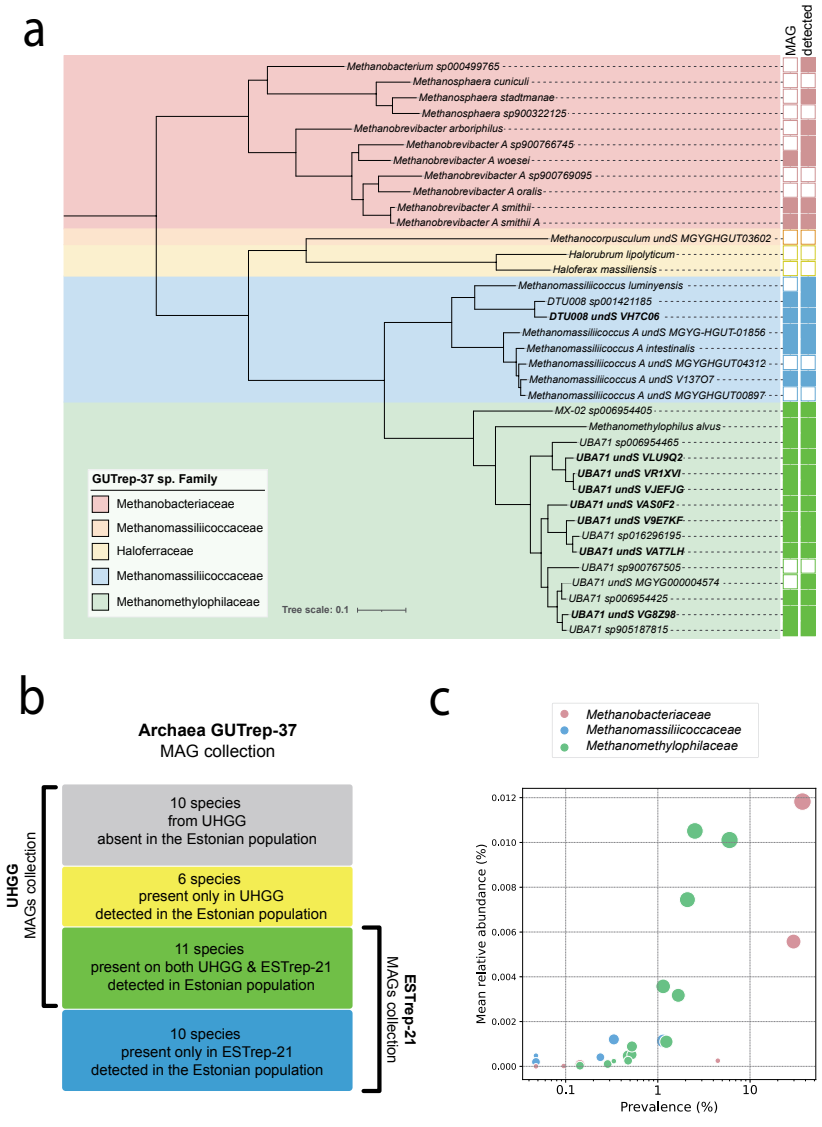

Figure 15. The phylogenetic tree, prevalence and abundance of the human gut archaea in Estonian population. **a.** FastTree approximate maximum-likelihood phylogenetic tree of human gut archaea, including species assembled in this study and those from the UHGG ("Archaea GUTrep-37" collection). The tree was constructed using multiple sequence alignments (MSAs) derived from the concatenation of 53 phylogenetically informative markers (arc53) with GTDB-Tk v2.3.0. Phylogenetic tree was constructed with FastTree and generated with iTOL (https://itol.embl.de), with midpoint rooting. Species are labelled with their respective names, while new species are named by their MAG_ID or UHGG_ID. Adjacent to each species label, two indicator boxes provide additional information: "MAG" – the presence or absence of an assembled MAG for the species in the Estonian population (filled and empty boxes, respectively), and "detected" – the detection of the species through mapping in the Estonian population (filled and empty boxes, respectively). Species are color-coded by their family affiliation: *Methanobacteriaceae*

(pink), *Methanomassiliicoccaceae* (blue), and *Methanomethylophilaceae* (green), *Methanocorpusculaceae* (orange), *Haloferacaceae* (yellow). **b.** Classification of species from "Archaea GUTrep-37" collection based on their origin and their presence in the Estonian population. **c.** Prevalence and abundance of archaeal species in the Estonian population. Species are color-coded by their family affiliation: *Methanobacteriaceae* (pink), *Methanomassiliicoccaceae* (blue), and *Methanomethylophilaceae* (green).

New species discovery rate

To assess whether the observed diversity approached saturation, we plotted the cumulative number of newly detected species against the number of samples included in genome reconstruction (**Figure 16**). Each additional set of 500 samples yielded approximately 70 new species, and no plateau was observed, suggesting that further genome reconstruction will likely continue to uncover previously undescribed diversity. Although this rate will inevitably be influenced by the ongoing expansion of global reference databases, the current trajectory indicates that genome reconstruction remains a productive approach for characterizing previously unrepresented microbial diversity.

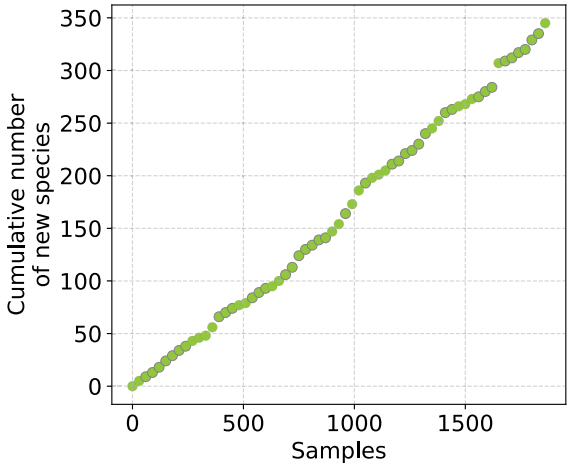

Figure 16. Relationship between the number of analysed samples and the cumulative number of new species identified.

4.2.3 Assembly-detection gaps

Most newly identified MAGs were represented by only one or two assemblies. For many of these species, prevalence estimated by read mapping was similarly low. However, some species exhibited substantially higher prevalence despite being reconstructed in only a few samples. We refer to this discrepancy between the number of samples in which a species was detected by read mapping and the number of samples in which a corresponding MAG was successfully reconstructed as the assembly–detection gap.

To quantify this effect across genera, an assembly-detection gap was calculated as:

$$\text{assembly–detection gap} = (N_{\text{detected}} - N_{\text{assembled}}) / N_{\text{detected}}$$

where N_{detected} represents the number of species detected by profiling and $N_{\text{assembled}}$ the number successfully reconstructed as MAGs. Values close to 1 indicate species that are frequently detected but poorly assembled.

However, some species retained large assembly-detection gaps despite frequent detection in metagenomic reads and moderate relative abundance (>1.5%). These findings suggest that limited assembly representation does not necessarily reflect rarity but may instead arise from biological or technical factors that hinder genome reconstruction, including strain-level complexity, uneven abundance distributions or high genomic similarity among closely related species.

Importantly, some under-assembled yet frequently detected species reached appreciable abundance levels, indicating that they may represent biologically relevant members of the microbiome despite limited representation in MAG collections. Their prevalence and abundance indicate potential functional relevance, underscoring the need to include such taxa in downstream microbiome association analyses despite their limited representation in MAG collections.

Species exhibiting particularly large assembly–detection gaps belonged to genera such as *Phocaeicola, Alistipes, Bacteroides*, CAG-603, CAG-269, *Stercorousia*, RGIG8607, *Mailhella, Nanosynbacter, Butyricimonas* and *Prevotella* (**Figure 17**).

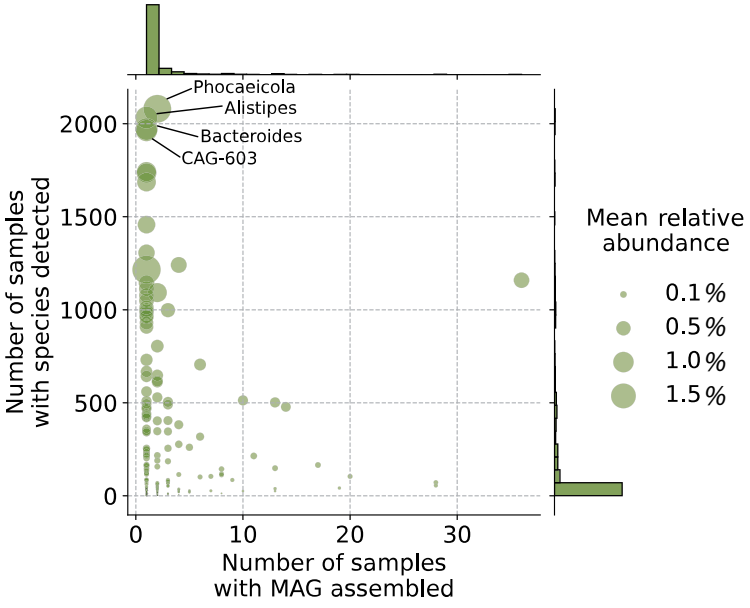

Figure 17. Relationship between the number of MAGs per species, prevalence estimated by read mapping, and mean relative abundance of newly identified species. Each point represents a species, with point size proportional to its mean relative abundance. Several species represented by only one or two MAGs exhibit high prevalence across the EstMB cohort while maintaining substantial mean abundance. (unpublished data)

To place these findings in context, the assembly–detection gap for previously assembled, known species can also vary widely. In contrast to many new species, some known species were represented by relatively large number of MAGs. Mean relative abundance among known species with small assembly–detection gaps was often similar to that of species with substantially larger gaps, suggesting that relative abundance alone does not explain differences in assembly success. Instead, successful genome reconstruction likely depends on taxon-specific genomic or ecological characteristics that influence assembly quality (**Figure 18**).

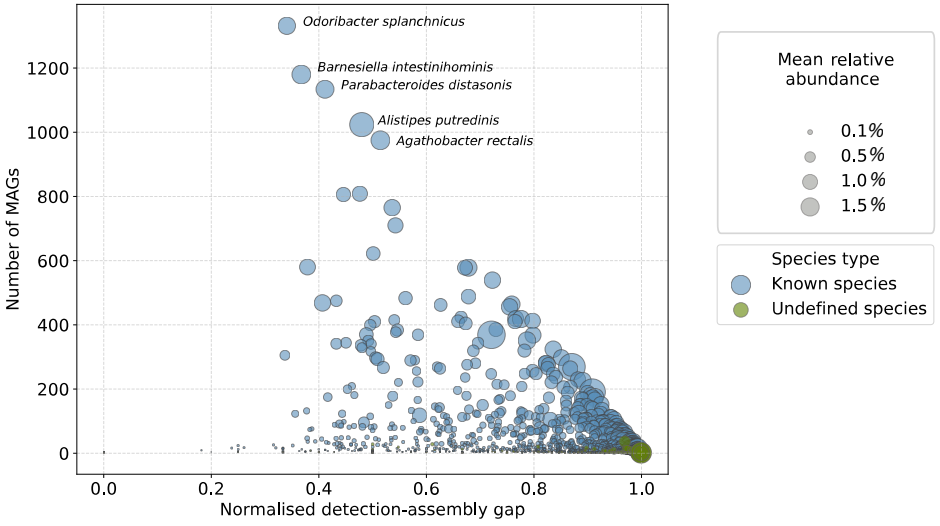

Figure 18. Relationship between the assembly-detection gap and the number of MAGs per species. Each point represents a species, with point size proportional to mean relative abundance. Blue points indicate known species, while green points indicate newly identified species. (unpublished data)

Species with small assembly–detection gaps and large number of reconstructed MAGs included *Odoribacter splanchnicus, Barnesiella intestinihominis, Parabacteroides distasonis, Alistipes putredinis, Agathobacter rectalis*, UBA11524 sp000437595, Ruminococcus_E bromii_B, Ruminococcus_D bicirculans, *Paraprevotella clara, Akkermansia muciniphila,* Limisoma sp000437795, Eubacterium_F sp003491505, *Parabacteroides merdae*, Lachnospira eligens_A, Ruminiclostridium_E siraeum and others.

4.2.4 Population-specific reference

Both newly reconstructed and previously described taxa from the Estonian population cohort were integrated into a population-specific MAG reference collection, EstMB-repMAG. This collection comprises 84,762 MAGs, representing 2,257 bacterial and 21 archaeal species.

Compared to global resources, our population-based EstMB-repMAG collection is approximately twofold smaller than the Unified Human Gastrointestinal Genome (UHGG) catalogue and fourfold smaller than the latest MetaPhlAn database. Because genome assembly does not recover all species present in a community, we hypothesized that a fraction of taxa in our samples remained undetected by assembly-based approaches.

To assess whether incorporating globally derived references improves microbiome profiling, species richness per sample was quantified using three reference databases:

(i) EstMB-repMAG collection (n = 2,278) profiled with CoverM.

(ii) Combined dereplicated UHGG and EstMB-repMAG collections (n = 4,792 species) profiled with CoverM.

(iii) MetaPhlAn4.1 database (8,609 species) profiled with MetaPhlAn.

Interestingly, the smallest, population-specific database yielded the highest number of detected species per sample (**Figure 19**). One possible explanation is that increasing database complexity elevates the frequency of multi-mapping reads, which are subsequently discarded during profiling due to ambiguous assignment, thereby reducing the number of confidently detected taxa.

These findings suggest that an effective reference database should balance comprehensive taxonomic representation with relevance to the target population. Excessively broad reference collections may introduce additional mapping ambiguity, which could reduce the number of confidently detected taxa.

Overall, these results challenge the prevailing strategy of continuously expanding global reference databases for universal application. Instead, population-specific reference collections may provide more accurate and sensitive taxonomic profiling for specific cohorts.

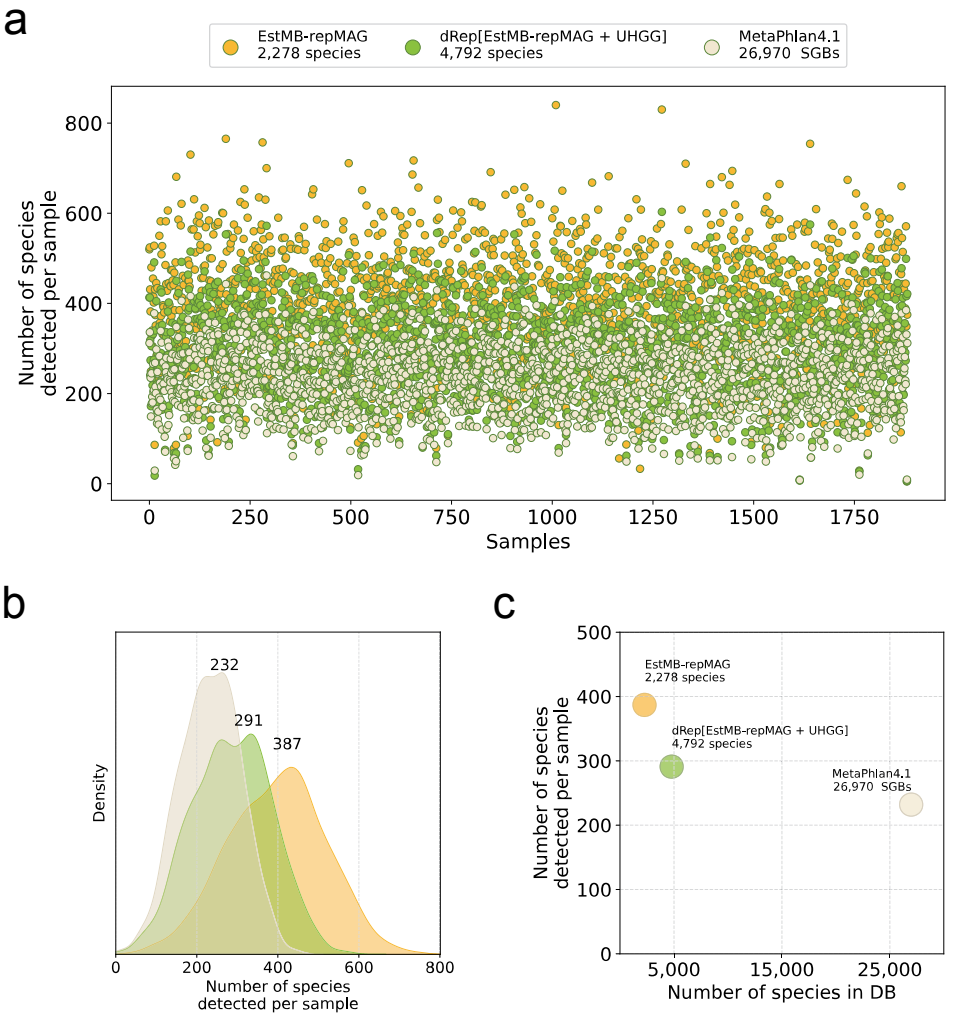

Figure 19. Comparison of species counts or species-level genome bins (SGBs) per sample obtained using different reference databases. **a.** Comparison of the number of species detected per sample with different profiling databases. **b.** Distribution of species counts per sample. Yellow indicates EstMB-repMAG, green indicates the dereplicated UHGG + EstMB-repMAG collection, and beige indicates MetaPhlAn4.1. Numbers above each density curve indicate the mean value of the corresponding distribution. **c.** Relationship between average number of species or SGBs detected per sample and the number of species or SGBs included in the profiling database (unpublished data)

4.2.5 Hidden within-species diversity

Beyond enabling the recovery of previously uncharacterized taxa, large-scale genome reconstruction also generates multiple genomes per species, thereby allowing the investigation of within-species variation. However, this representation is highly uneven across species.

In our dataset of 1,878 deeply sequenced samples, the number of meta-genome-assembled genomes (MAGs) per species varies widely. Most species (1,548; 68.6%) are represented by fewer than 100 MAGs, and a substantial fraction (1,037; 46.0%) by fewer than 10 MAGs. Such limited representation constrains the robust characterization of population structure and reduces statistical power for within-species analyses. As a result, within-species analysis are largely restricted to a relatively small subset of prevalent species for which sufficient numbers of MAGs were reconstructed and the assembly–detection gap was low.

The most extensively represented species, *Odoribacter splanchnicus*, was supported by 1,312 MAGs, followed by a sharp decline to approximately 400 MAGs per species and a more gradual decrease thereafter (**Figure 20**). Four species, *Odoribacter splanchnicus, Barnesiella intestinihominis, Parabacteroides distasonis*, and *Alistipes putredinis*, were each represented by more than 1,000 MAGs. These taxa were not only highly prevalent but also exhibited relatively low assembly–detection gaps. An additional six species were represented by more than 500 MAGs: *Agathobacter rectalis*, UBA11524 sp000437595 (a member of the class *Clostridia*), *Paraprevotella clara, Akkermansia muciniphila*, Limisoma sp000437795, and *Parabacteroides merdae*.

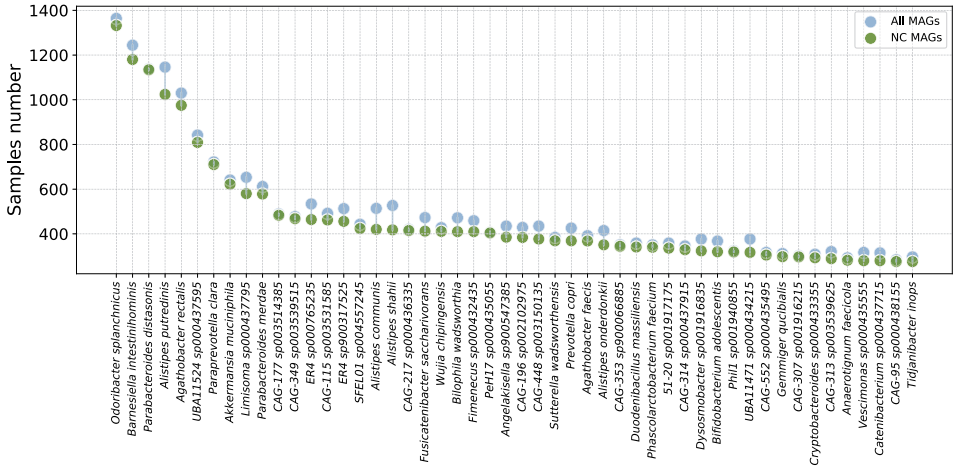

Figure 20. Number of MAGs and near-complete MAGs per species among the 50 species with the highest number of assembled MAGs. Blue dots represent the number of MAGs per species, and green dots represent the number of near-complete MAGs (NC MAGs) per species, defined as MAGs with completeness > 90%, contamination <5% according to CheckM2. (unpublished data)

After establishing that only a subset of species is sufficiently represented by reconstructed MAGs, the next step was to define what should be considered a meaningful within-species unit. To investigate within-species diversity, it is first necessary to define the principle by which genomes are grouped within a species. This is not a trivial issue, as the term “strain”, although widely used in the field, is applied inconsistently and often diverges from the definition established by the International Code of Nomenclature of Prokaryotes (Oren et al. 2023). Under the ICNP framework, a strain is defined as the direct descendant of a single bacterial cell and is therefore expected to have an almost identical genome.

The purpose of exploring within-species diversity is to identify genomic variation associated with specific phenotypic or ecological features. This requires grouping genomes into subpopulations of sufficient size to enable robust association analyses. Therefore, a concept is needed that captures **within-species genomic structure at an intermediate resolution**, broader than near-identical lineages, but finer than species-level classification. For this reason, the formal ICPN strain concept is not suitable for our analytical purpose.

As no existing term adequately describes clusters of genomes defined by a specified level of genomic similarity in the context of population-scale MAG association analysis, we introduce the term **genome unit** to denote such within-species groupings.

> ***Genome unit (GU)*** *– an operational within-species group consisting of genomes assigned to the same species that cluster together based on pairwise genomic similarity above a defined threshold.*

A key remaining question is the choice of an appropriate genome similarity threshold for defining GUs in human gut microbiome species. To address this, we computed a total of 6,942,981 pairwise average nucleotide identity (ANI) values across 376 species represented by more than 100 MAGs (**Figure 21**). The resulting distribution did not exhibit a clear discontinuity at high ANI values above 97% that would allow straightforward delineation of subspecies clusters, in contrast to the well-defined separation around ~95% that is typically used to define species boundaries. However, local minima in the distribution were observed at 95.9%, 96.8%, 98.1%, 99.0%, and 99.7%. The lower values are close to the conventional species boundary and are therefore too permissive, whereas 99.7% approximates a clonal-level definition and would likely yield groups that are too small for association analyses. Based on this, we selected an intermediate threshold of 99.0% ANI to define genome units. The threshold should be interpreted as a pragmatic analytical choice rather than a universal biological boundary.

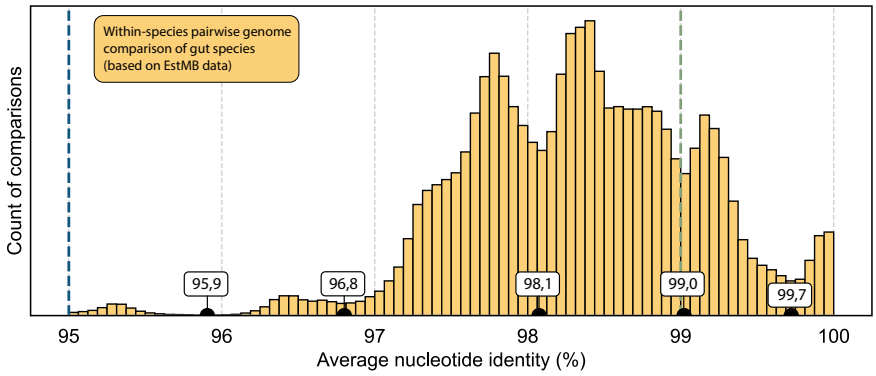

Figure 21. Histogram of within-species pairwise genome comparisons for 376 gut species, each represented by more than 100 MAGs reconstructed in the EstMB dataset. Local minima in the ANI distribution are indicated and were used to guide the selection of pragmatic treshold for genome unit definition (unpublished data)

We define within-species population structure as the set of genome units identified for each species, where each GU consists of genomes that cluster together at a pairwise similarity threshold of ANI ≥ 99.0%.

Within this framework, species diversity can be assessed by the number of GUs per species, referred to here as genome unit number (GUN). To account for differences in the numbers of reconstructed MAGs across species, we introduce both the raw number of genome units per species (GUN) and a normalized metric that scales GUN by the total number of MAGs, referred to as **normalised genome unit number** (nGUN).

GUN = Number of genome units

nGUN = (Number of genome units / Number of MAGs) × 100%

No consistent trend in normalized genome unit number (nGUN) was observed across gut microbial species. Instead, nGUN values varied widely, ranging from 0.4 to 94.0 (**Figure 22**), indicating substantial heterogeneity in within-species population structure.

At the lower end, *Odoribacter splanchnicus* exhibited an nGUN of 0.4, corresponding to approximately one genome unit per 250 MAGs, consistent with a highly cohesive population structure under the selected ANI threshold. In contrast, *Prevotella copri* showed one of the highest nGUN values, 94.0, reflecting its well-documented genetic heterogeneity, where nearly each MAG corresponds to a distinct genome unit. Notably, members of the Alistipes_A genus were observed at both extremes of the distribution, highlighting substantial variability even among closely related taxa.

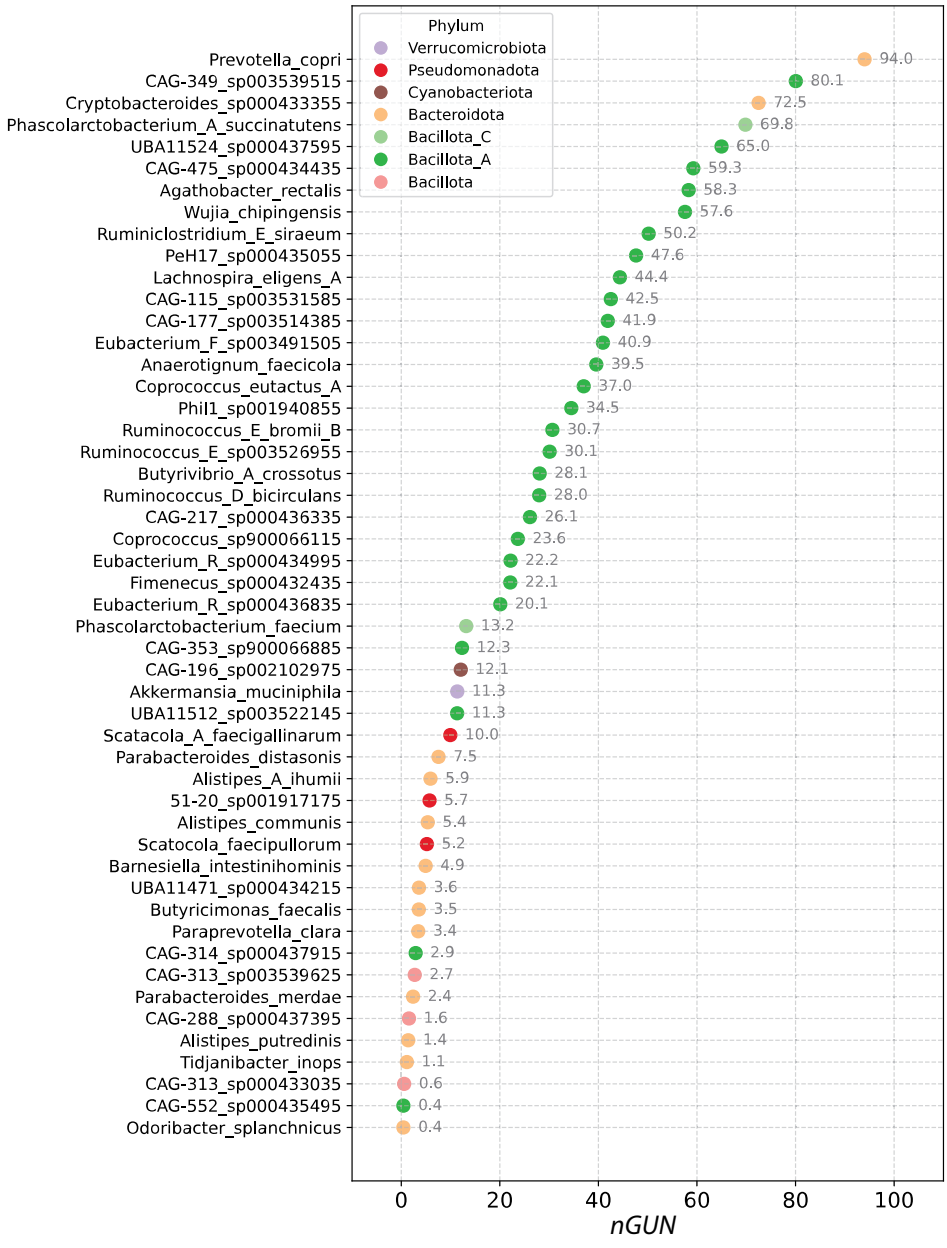

Figure 22. Normalized genome unit number (nGUN) values for the top 50 species with the highest number of metagenome-assembled genomes. nGUN was calculated as the number of genome units divided by the number of MAGs per species and multiplied by 100.

Genome units (GUs) are defined based on genomic similarity, a straightforward metric that can be efficiently computed across large-scale MAG datasets. However, in the context of our primary objective, which is to identify genome groups that differ in their associations with specific phenotypic or ecological features, it is essential to determine whether these GUs also exhibit functional differentiation.

Species with high nGUN values are, in practice, poorly suited for within-species association analyses. Their genomic diversity is distributed across many small units, often lacking sufficiently large subpopulations for meaningful statistical comparisons, regardless of the total number of reconstructed genomes. Such species are better described as exhibiting a continuum of genetic variation rather than discrete, well-defined groups. Conversely, low nGUN values do not necessarily imply low biological diversity, but rather indicate that, under the selected threshold, diversity is concentrated into fewer and larger genome units that are more suitable for association testing.

As mentioned above, within-species analyses are already constrained to a relatively small subset of prevalent species with a low assembly–detection gap, ensuring sufficient numbers of reconstructed MAGs. Our results indicate that an additional constraint must also be considered: low nGUN values are required to ensure the presence of genome units large enough for robust downstream comparisons.

Among the species with the highest numbers of reconstructed MAGs, only a subset meets this criterion. *Odoribacter splanchnicus* exhibited the lowest nGUN (0.4), followed by *Alistipes putredinis* (nGUN = 1.4) and *Parabacteroides merdae* (nGUN = 2.4), making them strong candidates for downstream within-species association analyses. In contrast, other species with similarly large numbers of reconstructed MAGs display high nGUN values and were therefore less suitable. Examples include *Agathobacter rectalis* (nGUN = 58.3), *UBA11524 sp000437595* (nGUN = 65.0), and *Limisoma sp000437795* (nGUN = 74.7).

To address this, we selected *Odoribacter splanchnicus* as a model species, as it represents the most suitable candidate for within-species association analyses based on our criteria: a high number of reconstructed MAGs, a low assembly–detection gap, and a low nGUN value. Within this species, we performed functional annotation of the two largest genome units GU-N1 and GU-N2. Although four GUs were identified in total, the remaining two contained too few genomes to support meaningful analysis and were therefore excluded (**Figure 23a**).

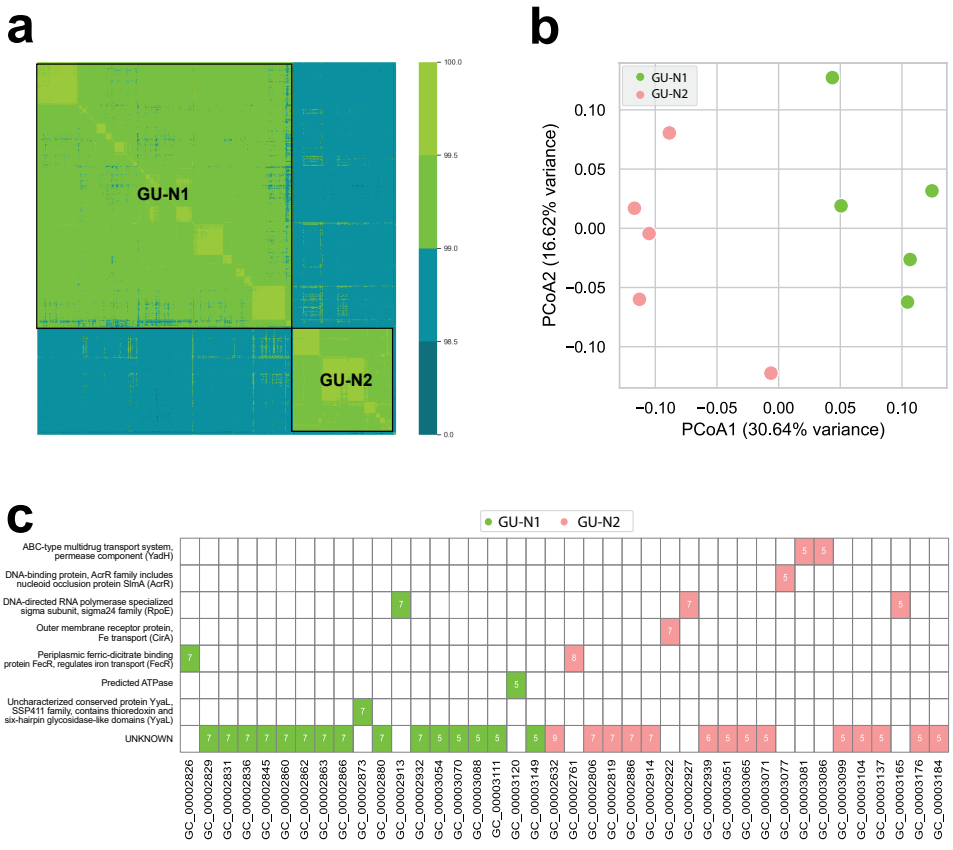

Figure 23. Genomic and functional variation across two major *O. splanchnicus* genome units. **a.** Heatmap of average nucleotide identity (ANI) values among *O. splanchnicus* MAGs, revealing two distinct genome units. **b.** Principal coordinates analysis (PCoA) of *O. splanchnicus* representative MAGs based on predicted gene cluster presence/absence profiles. **c.** Gene clusters uniquely present in only one of the two major *O. splanchnicus* genome units.

To explore functional differences, we performed a principal coordinates analysis (PCoA) of GU-N1 and GU-N2. As shown in **Figure 23b**, the two genome units were separated in the ordination space, indicating pronounced genomic differentiation at the level of gene content.

In total, 40 gene clusters were identified as unique to one of the two genome units (**Figure 23c**). While the majority of these clusters encoded hypothetical or uncharacterized proteins, several were assigned putative functions based on the Clusters of Orthologous Groups annotation framework. GU-N2 exhibited a broader repertoire of genes associated with stress response, iron acquisition, and antimicrobial resistance, features consistent with enhanced fitness under inflammatory conditions in the gastrointestinal tract. Notably, this included increased representation of the extracytoplasmic stress sigma factor RpoE (σ^E), iron uptake components such as FecR and CirA, and multidrug resistance determinants

including AcrR and an ABC-type efflux pump (YadH). In contrast, GU-N1 was enriched in proteins involved in redox homeostasis, such as YyaL/DsbD, suggesting a distinct adaptive strategy centered on oxidative stress mitigation.

Together, these results show that genome units defined by ANI-based clustering can also correspond to differences in gene content and predicted functional potential. This supports the use of GUs as biologically informative within-species units for downstream microbiome-host association analysis, while also emphasizing that their interpretation should remain species-specific and dependent on sufficient MAG representation.

4.2.6 Hidden within-species within-sample diversity

Apart from concerns related to completeness and contamination, a fundamental limitation of MAG-based analyses arises when multiple strains of the same species coexist within a single sample. Short-read assembly, which remains the most widely used approach in genome-resolved metagenomics, generally lacks the resolution to separate closely related strains. Instead of reconstructing distinct genomes, it may produce a consensus or **"composite" assembly** that predominantly reflects the most abundant strain genotype, while still incorporating signals from less abundant strains. As a result, these composite MAGs can obscure true within-sample strain diversity and may display intermediate genomic similarity patterns, depending on the relative abundance of the underlying strains and the genome regions incorporated into the assembly.

This limitation is particularly relevant for the interpretation of genome units. Composite MAGs may bias estimates of the genome unit number (GUN) per species, either by creating artificial intermediate genomes or by blurring the separation between otherwise distinct genome units. Consequently, the observed within-species population structure may partly reflect technical limitations of short-read assembly rather than true biological structure. Several approaches can mitigate this issue, including long-read sequencing–based assemblies, Hi-C–assisted metagenomics, single-cell genomics, or the integration of genome-resolved metagenomics with isolate sequencing. Nevertheless, short-read assemblies remain valuable for providing an initial, coarse-grained view of species structure, which can subsequently be refined using more advanced methodologies.

In some cases, the presence of multiple strains within a single sample may lead to fragmented assemblies that fall below MAG quality thresholds or **fail to be binned** into a coherent genome, resulting in the complete absence of a reconstructed genome for this particular species. If this pattern is consistent across samples, it can produce a pronounced assembly–detection gap. Such a gap may indicate species that tend to occur as diverse strain mixtures rather than as clonal populations, whereas species with minimal gaps are more likely to exist as relatively homogeneous populations or as populations dominated by a single strain per sample. However, the assembly-detection gap should not be interpreted as direct evidence of within-sample strain diversity on its own, as it may also

result from low abundance, uneven coverage, repetitive genomic regions, mobile genetic elements, high similarity to related species, or binning limitations.

Overall, within-sample within-species diversity represents an important hidden layer of microbial variation that is only partly captured by standard short-read MAG reconstruction. Recognizing this limitation is essential for interpreting both assembly-detection gaps and genome unit-based analysis, and highlighting the need for complementary methods to resolve strain mixtures within individual metagenomic samples.

4.3 Genome-resolved microbiome-wide association studies (MWAS) (Ref. II)

Our goal is to use genome-resolved metagenomes (GRM) to better understand how the microbiome relates to human health. A practical and accessible starting point toward this objective is association analysis, which enables the identification of links between microbiome composition and host phenotypes. While not definitive, this step provides a useful way to prioritize species that may be involved in underlying mechanisms, host-microbiome interactions or the development of predictive models.

GRM enables, first, the inclusion of newly reconstructed and previously uncharacterized species in MWAS and, second, within-species association analyses for a subset of species with high prevalence, low assembly–detection gaps, and low nGUN. Thus, GRM can extend microbiome-wide association studies beyond known reference species and beyond species-level resolution.

We leveraged the rich medical data available for the EstMB cohort and conducted MWAS across all prevalent diseases recorded in electronic health records (EHR) at both the species and within-species levels.

4.3.1 Species-level MWAS

For species-level MWAS, we selected diseases based on their prevalence in the cohort, including all conditions with more than 100 cases among the 2,504 individuals. This resulted in a set of 33 diseases, each defined using ICD-10 codes derived from EHRs linked to the Estonian Biobank cohort (**Ref. II, Supplementary Table S4**).

To limit the multiple testing burden, we restricted the analysis to species present in at least 1% of samples, yielding 1,595 species. In total, we identified 105 significant associations (Bonferroni-adjusted P value < 2.71×10^{-5}) involving 96 bacterial species across 25 diseases. Notably, newly assembled species contributed to associations with 8 of the 33 diseases. For example, one of the strongest associations with chronic ischemic heart disease was observed for a previously uncharacterized species within the genus *Nanosynbacter* species (ID: H2144_Nanosynbacter_undS; adjusted P value = 3.13×10^{-6}) (**Figure 24**). This

illustrates that population-specific genome reconstruction can reveal disease-associated microbial signals that would be missed or poorly resolved using only existing reference databases.

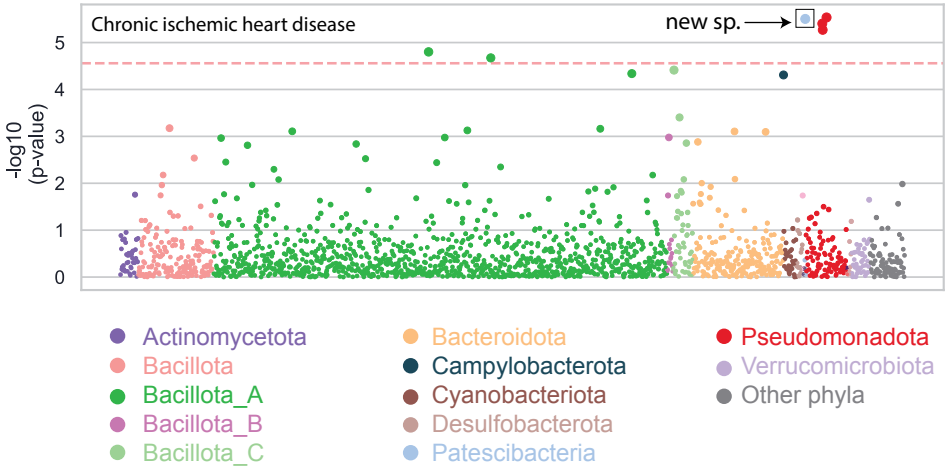

Figure 24. Metagenome-wide association results between EstMB-repMAG species abundance and chronic ischemic heart disease. Each data point corresponds to a single species, with vertical position reflecting the log-transformed P-value from the association model. Significant associations involving newly reconstructed species are highlighted with a box.

4.3.2 Within-species MWAS

For within-species MWAS, we selected *Odoribacter splanchnicus,* which stood out as the best candidate for within-species analysis based on our selection criteria (**Table 3**).

At the species level, *O. splanchnicus* did not show a significant association with any of the analysed diseases. To determine whether this species showed disease association at the within-species level, we performed logistic regression models testing the presence or absence of the two major *O. splanchnicus* units, GU-N1 and GU-N2, against the same 33 disease phenotypes previously analyzed in the species-level MWAS. Models were adjusted for BMI, age, and sex. This analysis identified a significant association between the presence of GU-N1 and two different diseases- gastritis and duodenitis, and hypertensive heart disease (**Figure 25**). The odds ratio for GU-N1 was below 1 for both diseases (gastritis and duodenitis OR = 0.56, hypertensive heart disease OR = 0.63). This indicates that the presence of GU-N1 was associated with lower odds of these diagnoses in the cohort. Importantly, this should be interpreted as an association rather than evidence of a causal protective effect.

Table 3. Characteristics of Odoribacter splanchnicus supporting its selection for within-species MWAS

Parameter	Value	Position among other species
Species prevalence	96%	Among the 3% most prevalent species
Number of MAGs	1332	Ranked first
Assembly-detection gap	23%	Among species with low assembly-detection gaps
GUN	4	Ranked first
nGUN	0.4	Lowest among analysed species

These results demonstrate that within-species MWAS can reveal associations that are not detectable at the species level. In the case of *O. splanchnicus,* the species as a whole showed no significant disease associations, whereas one of its genome units was significantly associated with two disease phenotypes. This finding supports the central premise that species-level microbiome profiling can mask biologically relevant within-species heterogeneity, and that genome unit-based analysis may improve the resolution of microbiome-health association studies.

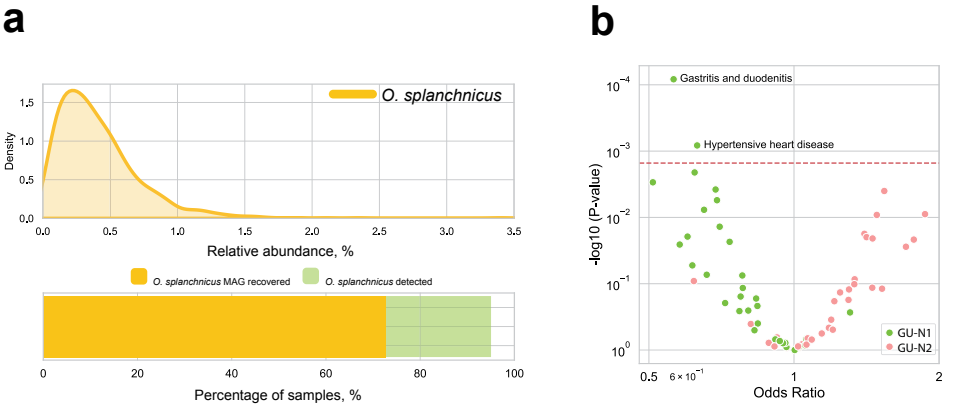

Figure 25. Within-species MWAS of *Odoribacter splanchnicus.* **a.** *O.splanchnicus* relative abundance, number of recovered MAGs and prevalence across samples. **b.** Volcano plot of associations between the two major *O. splanchnicus* genome units and 33 disease phenotypes. The red line indicates the Bonferroni-corrected significance threshold.

4.4 Next challenges to overcome

The study of within-species diversity is still in its early stages. A deeper understanding of how bacterial species are internally structured, together with the resolution of current technical limitations in metagenomic assembly, will be essential for advancing the field. Advancing this area will be essential for moving microbiome research beyond descriptive analysis toward a mechanistic understanding of microbial community function and host-microbiome interactions.

4.4.1 Resolving within-species population structure

A major challenge for future studies will be to determine how within-species diversity is structured. Even among species inhabiting relatively stable environments, such as the human gut, species differ markedly in their population structure. Some species harbour large, well-separated genomic clusters, whereas others exhibit more continuous variation, with little or no obvious clustering (**Figure 26**). Using the data from the Estonian Microbiome cohort (EstMB), we observed that, *Odoribacter splanchnicus* shows several large, clearly separated within-species clusters that can be distinguished using an ANI threshold of approximately 99.0% (**Figure 26a**). In contrast, *Agathobacter rectalis* displays even more pronounced cluster separation, but the relevant boundary occurs at a much lower ANI threshold, around 97.6%. Applying a standard ANI threshold of 99.0% to this species fails to recover the biologically meaningful larger clusters, instead fragmenting the species into many small genomic units (**Figure 26b**). A similar pattern is observed for *Akkermansia muciniphila,* where the major within-species clusters are separated at approximately 97.7% ANI (**Figure 26c**). For some other species, such as UBA11524 sp000437595, the situation is less clear, and it remains uncertain whether discrete within-species genomic units can be identified at all (**Figure 26d**).

These examples are preliminary and should be interpreted with caution. They nevertheless illustrate an important point: within-species structure varies substantially between bacterial species and cannot always be captured by a single universal ANI threshold. In the future, a more systematic, careful, and detailed analysis of within-species structure across a broad range of bacterial species will be needed.

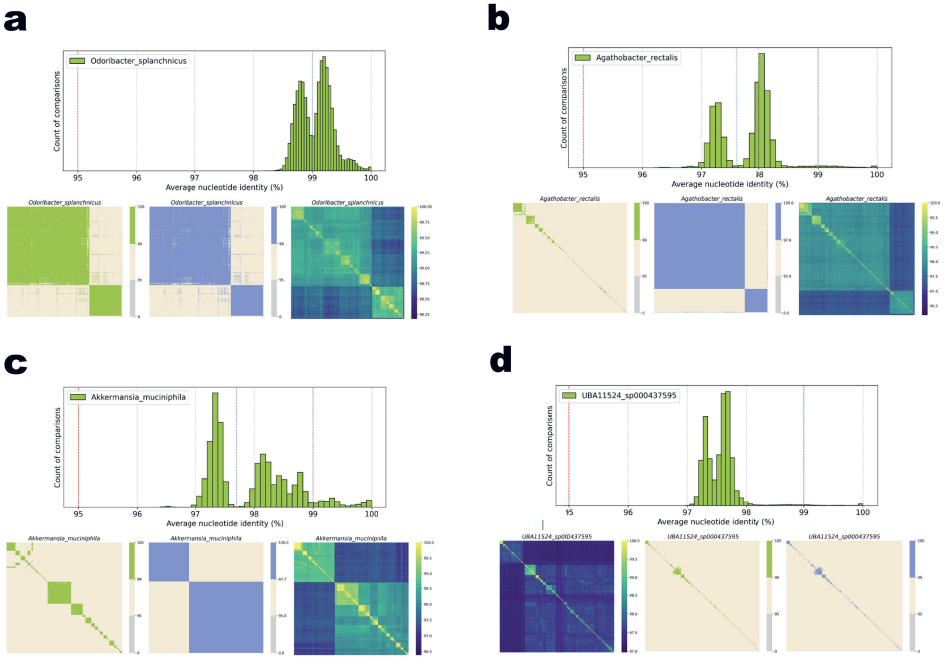

Figure 26. Examples of within-species population structure in selected gut bacterial species reconstructed from the Estonian Microbiome (EstMB) cohort MAG database. (unpublished data)

4.4.2 Reconsidering the species concept

These observations suggest that future work should move toward species-specific frameworks for defining within-species populations. Such frameworks should integrate multiple dimensions of variation, including nucleotide similarity, accessory genome composition, and functional potential. A key open question is whether genomic clusters identified in this way correspond to biologically meaningful units, such as populations with distinct ecological roles or host associations.

This question is particularly important for microbiome-wide association studies (MWAS), where biologically relevant signals may reside below the species level and remain undetected in species-based analyses. Resolving within-species structure therefore has the potential to substantially improve the resolution and interpretability of microbiome–host association studies.

Such frameworks would provide a more realistic view of bacterial species as structured and variable genomic populations, rather than as homogeneous taxonomic entities (**Figure 27**).

Developing robust frameworks for identifying these units represents a key challenge for future microbiome research.

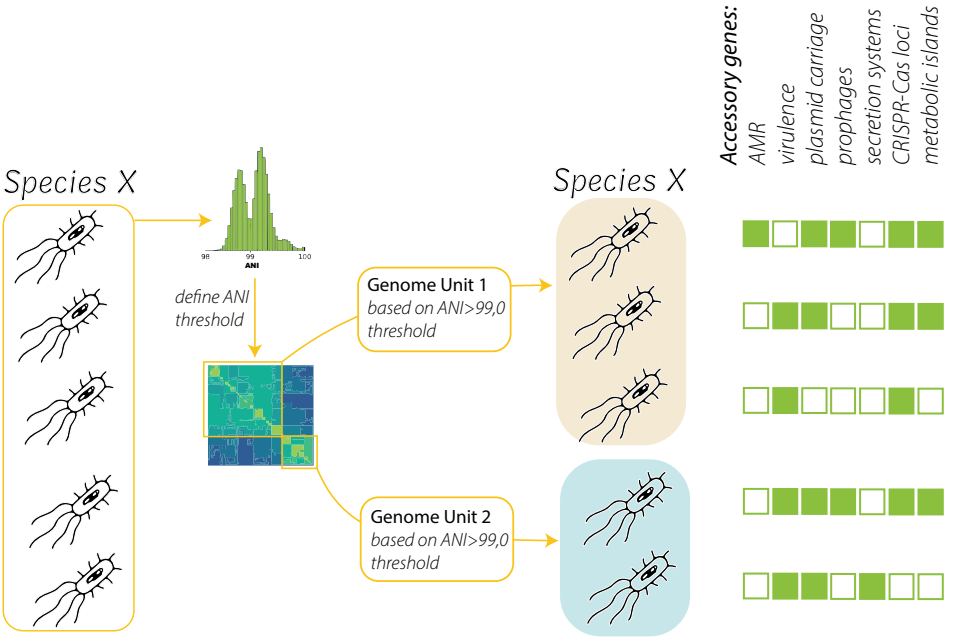

Figure 27. Schematic representation of bacterial species as a structured and genomically variable population. Authors' own work.

CONCLUSIONS

Therefore, the main conclusions drawn from this thesis are as follows:

- The two major short-read sequencing platforms used for metagenomic sequencing are broadly compatible for taxonomic profiling and can be applied to complementary samples from the same cohort. However, functional profiling was more sensitive to platform-related differences, indicating that taxonomic concordance does not necessarily imply equivalent functional profiles.
- Population-specific MAG reference databases can improve microbiome profiling by balancing taxonomic coverage with relevance to the target cohort. In this work, the EstMB-repMAG collection provided a cohort-specific reference resource that incorporated both newly reconstructed and previously described taxa from the Estonian population.
- Databases of reconstructed bacterial and archaeal MAGs represent a valuable resource for microbiome research. They provide an essential foundation not only for association studies but also for investigating fundamental biological questions, including the nature of within-species diversity. The recovery or archaeal MAGs further highlights that archaeal diversity in the human gut remains underrepresented in current reference collections.
- Genome-resolved metagenomics revealed multiple hidden layers of microbial diversity, including previously uncharacterized species, within-species genomic structure, and within-sample strain-level complexity that is only partly resolved by standard short-read MAG reconstruction. These findings emphasise both the value and the current limitations of short-read-based genome reconstruction.
- In this work, we identified significant disease associations at the species level, developed a framework for selecting species suitable for within-species analysis, and demonstrated that functionally distinct genomic units within a species can be associated with disease in ways that are not detectable at the species level alone. This supports the use of genome-unit-level analysis as a complementary strategy to species-level MWAS for improving the resolution of microbiome-health association studies.

SUMMARY IN ESTONIAN

Mikrobioomi genoomipõhine analüüsi: võimalused ja väljakutsed

Soolestiku mikroorganismid, sealhulgas bakterid ja arhed, on inimese tervisega tihedalt seotud. Nad võivad mõjutada peremeesorganismi ainevahetust, lagundada muidu seedimatuid toidukomponente, toota immuunsust mõjutavaid metaboliite ning aidata kaitsta organismi patogeenide eest. Samas võivad mõned mikroobsed protsessid kahjustada soole limabarjääri või viia selliste ühendite tekkeni, mis on seotud põletiku ja haigustega. Seetõttu on mikrobioomi koosseisu ja funktsiooni täpsem kirjeldamine oluline inimese tervise mõistmiseks.

Viimastel aastatel on genoomipõhine metagenoomika oluliselt muutnud mikrobioomiuuringuid. See lähenemine võimaldab rekonstrueerida mikroobide genoome otse keerukatest kooslustest ilma mikroobe kultiveerimata. Sellisel viisil saadud metagenoomi abil kokku pandud genoomid ehk MAG-id on avanud suure hulga varem kirjeldamata mikroobset mitmekesisust ning näidanud, et ka juba tuntud bakteriliikide sees võib esineda ulatuslik genoomne varieeruvus. Seetõttu pakub genoomipõhine metagenoomika võimalust uurida nii uusi liike kui ka liikide sisemist struktuuri ning hinnata, kas traditsiooniline liigitaseme käsitlus on piisav mikrobioomi ja tervise vaheliste seoste uurimiseks.

Selles väitekirjas kasutasin Eesti Mikrobioomi kohordi andmeid, mis hõlmavad 2504 Eesti Geenivaramu osaleja soolestiku metagenoomseid andmeid. Töö eesmärk oli hinnata genoomipõhise metagenoomika võimalusi ja piiranguid inimese soolestiku mikrobioomi kirjeldamisel ning mikrobioomi ja tervise vaheliste seoste leidmisel.

Töö esimeses osas võrdlesin kahe lühikeste lugemite sekveneerimisplatvormi, NovaSeq 6000 ja MGISEQ-2000, tulemusi. Taksonoomilised profiilid olid platvormide vahel üldiselt hästi võrreldavad, mis näitab, et eri platvormidel genereeritud andmeid saab sama töövoo ja referentsandmebaaside kasutamisel taksonoomiliseks profiilimiseks koos analüüsida. Funktsionaalne profiilimine oli aga platvormiga seotud erinevuste suhtes tundlikum. MGI andmetes tuvastati rohkem funktsionaalselt annoteeritud lugemeid, viidates sellele, et funktsionaalsete geenide ja radade tuvastamine sõltub rohkem sekveneerimissügavusest, järjestusraamatukogu keerukusest ja genoomi katvuse ühtlusest.

Töö teises osas rekonstrueerisin sügavalt sekveneeritud EstMB-deep andmestikust mikroobseid genoome ning lõin Eesti populatsioonile kohandatud MAG-referentsandmebaasi. See andmebaas, EstMB-repMAG, sisaldab nii varem tuntud kui ka Eesti kohordis rekonstrueeritud uusi mikroobseid liike. Populatsioonispetsiifiline referentsandmebaas parandas mikrobioomi profileerimist. Lisaks bakteritele võimaldas täiendav arhedele suunatud analüüs rekonstrueerida inimese soolestiku arhede MAG-e, mis näitab, et arhede mitmekesisus on praegustes referentskogudes endiselt alakaetud.

Genoomipõhine metagenoomika paljastas mitu varjatud mikroobse mitmekesisuse tasandit. Esiteks tuvastati varem kirjeldamata liike, mida olemasolevad

referentsandmebaasid ei esindanud. Teiseks võimaldas suur hulk sama liigi MAG-e uurida liikide sisemist genoomset varieeruvust. Tulemused näitasid, et bakteriliigid ei ole alati homogeensed üksused, vaid võivad koosneda mitmest selgelt eristatavast genoomsest alarühmast. Kolmandaks ilmnes, et ühe proovi sees võib sama liigi piires esineda mitu lähedast tüve või genoomset varianti, mida standardne lühikeste lugemite põhine MAG-rekonstruktsioon lahendab ainult osaliselt. Need tulemused rõhutavad nii genoomipõhise metagenoomika väärtust kui ka selle praeguseid tehnilisi piiranguid.

Töö kolmandas osas kasutasin EstMB kohordi elektrooniliste tervise-andmetega seotud infot, et uurida mikrobioomi ja haiguste vahelisi seoseid. Liigitaseme mikrobioomiülene assotsiatsiooniuuring tuvastas mitmeid olulisi seoseid bakteriliikide ja haiguste vahel, sealhulgas seoseid ka varem kirjeldamata liikidega. See näitab, et kohordispetsiifiline MAG-andmebaas võib avada haigustega seotud mikroobseid signaale, mis jääksid tavapäraste referentsandmebaasidega märkamatuks või halvasti kirjeldatuks.

Lisaks arendasin välja raamistiku liikide valimiseks liigisisese assotsiatsiooni-analüüsi jaoks. Selle lähenemise abil näitasin, et ühe bakteriliigi sees olevad genoomsed üksused võivad olla haigustega seotud viisil, mida kogu liigi tasemel analüüs ei tuvasta. Näiteks *Odoribacter splanchnicus* ei näidanud liigitasemel olulisi haigusseoseid, kuid selle ühe genoomse üksuse esinemine oli seotud kahe haigusfenotüübiga. See toetab ideed, et liigitaseme profiilimine võib varjata bioloogiliselt olulist liigisisest heterogeensust ning et genoomsete üksuste tasemel analüüs võib parandada mikrobioomi ja tervise vaheliste seoste lahutusvõimet.

Kokkuvõttes näitab see väitekiri, et genoomipõhine metagenoomika võimaldab liikuda mikrobioomi kirjeldamiselt suurema bioloogilise lahutusvõimega analüüside poole. Populatsioonispetsiifilised MAG-referentsandmebaasid parandavad mikrobioomi kirjeldamist, aitavad tuvastada varem kirjeldamata mikroobset mitmekesisust ja loovad aluse liigisisese struktuuri uurimiseks. Tulevikus on vaja paremaid eksperimentaalseid ja bioinformaatilisi meetodeid, sealhulgas sügavamat sekveneerimist, kvaliteetsemaid referentsandmebaase, pikemate lugemite kasutamist ja süstemaatilisemat lähenemist liigisiseste genoomsete üksuste määratlemisele. Sellised arengud aitavad muuta mikrobioomiuuringud täpsemaks ja bioloogiliselt tõlgendatavamaks ning võivad parandada meie arusaamist mikrobioomi rollist inimese tervisele.

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In March 2022, I had no idea what I was going to do next. I knew only one person in Estonia, my landlady, Merike. Merike showed me one of the most impressive sides of Estonia: the power of community. I needed a job, so Merike wrote about me on Facebook, and somehow her post reached the Tartu Biobank. I was invited for an interview. Thank you, Merike. It is probably because of you that I am a researcher now.

I came to Tartu by train and saw the Institute of Genomics for the first time. There, I met Lili, who introduced me to my current PI, Elin, showed me the Aparaat, and bought me soup for lunch. I remember that this was the first time I thought that everything was going to be okay. Thank you, Lili!

Soon, I joined the Tartu microbiome group and started working on bacterial genome reconstruction under Elin's supervision. I was very lucky because Elin turned out to be the best PI anyone could have. Elin, I want to thank you for so many things. Thank you for the care I always felt, not only at work but also outside the office. I always knew that if I faced a problem, I would not be completely alone and could ask you for help. That meant a lot to me. Despite being extremely busy, you always managed to find time for me and listen to both my project ideas and my concerns about everything else. Thank you for never pressuring me to follow the original plan and instead giving me the freedom to develop the project in the directions I found interesting. Thank you also for supporting my side projects. Whenever I wanted to attend a conference, summer school, or research visit, you supported me. You not only helped make these trips possible but also introduced me to interesting people and made conference travel not only useful, but also fun.

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I have always loved data analysis. I remember that when I was a child, my father showed me Excel and taught me how to calculate salaries for several people in it. I was fascinated and played with it for days. Writing, however, was a skill I had to develop during my PhD. The writing retreats organized by our institute were an enormous help. The simple idea of leaving the office and dedicating almost an entire week only to writing, without allowing yourself to be distracted by other tasks, is a game changer for someone like me, who started by struggling to write even a single sentence. Thank you, Monika, for organizing these retreats. I wrote all my papers during them.

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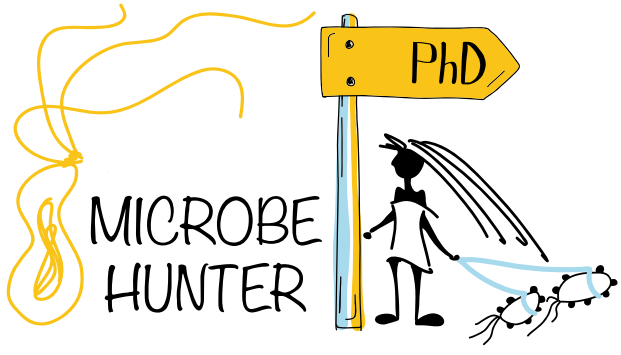
Finally, I want to thank my parents. They are very different, and I feel that I am a mixture of their different characters. Thank you for supporting me, believing in me, and never forcing me to follow the path you wanted instead of the one I wanted. I am very lucky to have parents like you.



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Popular science articles:

Kateryna Pantiukh (2024). Hidden bacteria may shape your health. Research in Estonia https://researchinestonia.eu/2024/10/24/bacteria-and-genome/

Kateryna Pantiukh (2023). Tartu genomic researcher finds 300 new bacterial species. Novaator. https://news.err.ee/1609141072/3-minute-lecture-tartu-genomic-researcher-finds-300-new-bacterial-species

Supervised dissertations:

Oleksandr Kholonivskyi	Bachelor's Degree, Institute of Genomics, University of Tartu, Estonia, 2026, "Characterizing the genomic diversity of prevalent gut microbiome bacterial species using metagenome-assembled genomes"
Vanessa Viiding	Bachelor's Degree, Institute of Genomics, University of Tartu, Estonia, 2026, "Arhede tuvastamist mõjutavad tegurid inimese soolestiku mikrobioomi uuringutes" and in english "Factors influencing the detection of archaea in human gut microbiome studies"

Awards and scholarships:

2025 **The 1st Prize for the best poster presentation**
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2025 **Acknowledgement for the best poster presentation in microbiology**
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2025 **EMBO|EMBL Symposium travel grant**
EMBO | EMBL Symposium: The human microbiome taking place at EMBL Heidelberg (€400)

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2024 **Artur Lind Scholarship**
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2024 **Audience award for the Best Talk**
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2024 **Winner of the PhD student competition**
Training Camp 2024: The Art of Giving a Popular Science Talk

2024 **Erasmus+ Scholarship Grant**
Erasmus+EU programme for education, training, youth and sport (€2,100)

2024 **Estonian Doctoral School mobility grant**
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Pantiukh, K.; Aasmets, O.; Krigul, K. L.; Org, E. (2026). Metagenome-assembled genomes from a population-based cohort uncover novel gut species and within-species diversity, revealing prevalent disease associations. mSystems, e00114-26. DOI: 10.1128/msystems.00114-26.

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Vanessa Viiding	Bakalaureusekraad, Tartu Ülikooli Genoomika Instituut, 2026, "Arhede tuvastamist mõjutavad tegurid inimese soolestiku mikrobioomi uuringutes" and in english "Factors influencing the detection of archaea in human gut microbiome studies"

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