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# Genomic Islands Confer Heavy Metal Resistance in *Mucilaginibacter kameinonensis* and *Mucilaginibacter rubeus* Isolated from a Gold/Copper Mine

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**Abstract:** Heavy metals (HMs) are compounds that can be hazardous and impair growth of living organisms. Bacteria have evolved the capability not only to cope with heavy metals but also to detoxify polluted environments. Three heavy metal-resistant strains of *Mucilaginibacter rubeus* and one of *Mucilaginibacter kameinonensis* were isolated from the gold/copper Zijin mining site, Longyan, Fujian, China. These strains were shown to exhibit high resistance to heavy metals with minimal inhibitory concentration reaching up to 3.5 mM Cu<sup>(II)</sup>, 21 mM Zn<sup>(II)</sup>, 1.2 mM Cd<sup>(II)</sup>, and 10.0 mM As<sup>(III)</sup>. Genomes of the four strains were sequenced by Illumina. Sequence analyses revealed the presence of a high abundance of heavy metal resistance (HMR) determinants. One of the strain, *M. rubeus* P2, carried genes encoding 6 putative P<sub>IB-1</sub>-ATPase, 5 putative P<sub>IB-3</sub>-ATPase, 4 putative Zn<sup>(II)</sup>/Cd<sup>(II)</sup> P<sub>IB-4</sub> type ATPase, and 16 putative resistance-nodulation-division (RND)-type metal transporter systems. Moreover, the four genomes contained a high abundance of genes coding for putative metal binding chaperones. Analysis of the close vicinity of these HMR determinants uncovered the presence of clusters of genes potentially associated with mobile genetic elements. These loci included genes coding for tyrosine recombinases (integrase) and subunits of mating pore (type 4 secretion system), respectively allowing integration/excision and conjugative transfer of numerous genomic islands. Further in silico analyses revealed that their genetic organization and gene products resemble the *Bacteroides* integrative and conjugative element CTnDOT. These results highlight the pivotal role of genomic islands in the acquisition and dissemination of adaptive traits, allowing for rapid adaptation of bacteria and colonization of hostile environments.

**Keywords:** *Mucilaginibacter rubeus*; *Mucilaginibacter kameinonensis*; genomic island; evolution; heavy metal resistance; draft genome sequence; CTnDOT

## 1. Introduction

Heavy metals (HMs) have a dualistic impact on living organisms. On the one hand, metal ions are essential for numerous biological processes mandatory for cellular activity, including homeostasis, enzyme activity, and protein functionality [1]. On the other hand, when present in excess in the environment, HM can have toxic effect hindering diverse cellular processes and thus cellular life.

Heavy metal pollution has been part of Earth's history as it can originate from natural processes such as volcanic eruption. Recent (over)industrialization and exploitation of Earth resources worldwide has accelerated HM release into the environment and led to high levels of water, air, and soil pollution. Especially, mine exploitation for metal extraction is one of the most important sources of heavy metal pollution [2]. This comes not only from excavating deep-buried HMs to be exposed to the surface, but also from extraction protocols that often rely on the use of other contaminants, including HMs [2].

Beyond its effects on people, HM toxicity was shown to have profound impacts on microbial communities, including fungi and bacteria [2]. Heavy metals were shown to have critical consequences on bacterial viability due to their pleiotropic effect on cellular processes. Excess of HM can disrupt the cell membrane, damage nucleic acids and proteins, impair enzymatic activities, and inhibit key processes such as transcription [1]. The presence of HM pollution exerts a high selective pressure on microbial communities, reducing their diversity, biomass, and activity, thus strongly impacting the biological activity of polluted environments [3].

In order to cope with the presence of elevated concentration of HMs, a myriad of bacterial genetic programs has been selected encoding functions that allow efflux and/or sequestration of HMs, and modification to inactivate or reduce reactivity of certain metal ions. The main mechanism to resist toxicity of HMs is efflux [1]. Important classes of HM transporters include P<sub>1B</sub>-type ATPases and cation diffusion facilitators (CDF). Both types of transporters translocate HM ions from the cytoplasm across the cytoplasmic membrane into the periplasm [4]. In the context described here with microbes having to handle very high external concentrations of HMs, P-type ATPases are much more relevant since they are much more powerful using ATP to pump HMs against their concentration gradient out of the cytoplasm [5]. In addition, HMs are translocated from the periplasm across the outer membrane into the extracellular space by resistance-nodulation-division (RND)-type transport systems. These multicomponent transporters of the RND type contain 3 RND transport proteins, 6 membrane fusion proteins (MFPs), and 3 outer membrane factor (OMF) proteins. The fascinating transport mechanism of the RND-type transport complex has been described in detail [4]. P<sub>1B</sub>-type ATPases and RND-type transport systems were described as being the most important systems to confer a high HM resistance (HMR).

Bacteria also show an astonishing capability to spread HMR genes within bacterial communities via horizontal gene transfer. Dissemination of genetic material conferring HMR is frequently associated with conjugative plasmids, genomic islands, and transposons [6]. Conjugative plasmids are extrachromosomal replicative entities able to transfer from a donor cell toward a recipient cell by conjugation [7]. Conjugative plasmids have been recognized as major contributors for the spread of adaptive traits such as antibiotic resistance, new metabolic capacities, and HMR [8]. Conjugative plasmid-borne HMR is associated with occurrence of large clusters of HMR genes that can span over several kb [9–15]. Portions of genomic DNA called genomic islands (GIs) were also shown to play a pivotal role into the horizontal dissemination of genetic material [16]. Although the mechanisms underlying the mobility of some GIs remain obscure, current knowledge describes different strategies that ultimately rely on conjugative transfer [17,18]. GI-associated HMR was described in *Enterobacteriaceae* and *Shewanellaceae* [19], *Listeria monocytogenes* [20], and *Acinetobacter baumannii* [21]. Also, HMR was shown to be conferred by an IncC-dependent mobilizable genomic island SGI1 variant called SGI1-K in *Salmonella enterica* [22–24]. Transposons are genetic entities able to move intra-molecularly (on the same replicon) or inter-molecularly (between different replicons) [25]. Most transposons can hitchhike by integrating into a conjugative plasmid or a GI for intercellular mobility. Transposons conferring HMR were described to be in association with other mobile genetic elements [13,22].

In this study, we describe the isolation and characterization of four heavy metal-resistant *Mucilaginibacter* strains isolated from a gold/copper mine in China. Genomes of these strains were sequenced and further in silico analysis revealed a high number of heavy metal resistance determinants. Moreover, at least part of these HMR gene clusters were shown to be potentially mobile as they are in the close vicinity of the core region of putative integrative and conjugative elements (ICEs).

## 2. Materials and Methods

### 2.1. Bacterial Isolation

Strains *Mucilaginibacter rubeus* P1, P2, and P3 were isolated from samples collected at 5–10 cm below the surface of a soil located near a waste water treatment dam of a copper-gold mine, and *Mucilaginibacter kameinonensis* P4, was isolated from a hillside with little human activity within the gold and copper mine (Zijin mining) in Longyan city of Fujian province, China (Table 1). After serial dilutions with 0.85% NaCl, the soil sample was spread on R2A (DSM medium 830) agar plates containing 2 mM  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ . After incubation at 28 °C for 1 week, the strains were isolated and later stored at –80 °C in 20% glycerol (*w/v*).

**Table 1.** Characteristics of the heavy metal (HM)-contaminated soil from where the strains were isolated.

	<i>Mucilaginibacter kameinonensis</i> P4	<i>Mucilaginibacter rubeus</i> P3	<i>M. rubeus</i> P2	<i>M. rubeus</i> P1
Altitude (m)	216	192	192	192
Longitude	N25°09.719'	N25°09.724'	N25°09.724'	N25°09.724'
Latitude	E116°23.258'	E116°23.258'	E116°23.258'	E116°23.258'
pH	6.64	5.52	6.32	6.32
Water content	9.38%	6.41%	7.05%	7.05%

### 2.2. Taxonomic Analysis

Strains were incubated at 28 °C for 24 h on R2A agar plates. As described in Brosius et al. [26], the universal primer pair 27F/1492R was used to amplify 16S sequences and the amplified PCR product was subsequently sequenced [26]. PCR products were sequenced by Biosune Company (Fuzhou, China) using the Sanger method. Based on the EzTaxon database (<http://eztaxon-e.ezbiocloud.net>) [27], pairwise sequence similarity and phylogenetic neighbors of the sequences of each individual strain (1382–1432 bp) were obtained through BLAST searches. In total, 19 *Mucilaginibacter* strains with publicly available 16S ribosomal RNA (rRNA) gene sequences were selected, with *Pedobacter africanus* DSM 12126T (AJ438171) as an out-group, to do the alignment via Mega 7.0 software [28]. A Neighbor-joining (NJ) tree was generated and the Kimura's two-parameter model was used to calculate evolutionary distances [29], and bootstrap analysis with 1000 replications was conducted to obtain confidence levels of the branches [30].

### 2.3. Determination of the Minimal Inhibitory Concentration

To determine the level of resistance to various metals of all strains, *M. rubeus* P1, P2, and P3 and *M. kameinonensis* P4 were grown on Cu, As, Cd, and Zn agar plates containing different  $\text{Cu}^{(II)}$ ,  $\text{Zn}^{(II)}$ ,  $\text{As}^{(III)}$ , and  $\text{Cd}^{(II)}$  concentrations to determine the minimal inhibitory concentration (MIC). The different R2A plates contained 0–10.0 mM of copper or arsenic, with 0.5 mM increments, 0–30.0 mM with 1.5 mM increments in case of zinc, and 0–2.0 mM cadmium with the increments being 0.2 mM. 1M  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ,  $\text{ZnCl}_2$ ,  $\text{NaAsO}_2$ , and  $\text{CdCl}_2 \cdot 5\text{H}_2\text{O}$  stock solutions were prepared and stored after filtration through a 0.22  $\mu\text{m}$  filter.

#### 2.4. Cell Morphology and Flagella Observation

Overnight cultures of strains *M. rubeus* P1, P2, and P3 and *M. kameinonensis* P4 were inoculated into 50 mL of R2A medium at 28 °C with 180 rpm shaking. After 24 h of growth with shaking, cells were centrifuged (1000× *g*, 10 min, 4 °C) and observed under scanning electron microscopy (SEM). Cells were harvested and washed three times with cold (4 °C) phosphate buffered saline (0.2 M PBS, pH 7.2). Fixation was performed with 2.5% glutaraldehyde (24 h, 4 °C). Fixed cells were dehydrated through a series of alcohol dehydration steps (30%, 50%, 70%, 85%, 95%, and 100%) and finally freeze dried and sputter coated. The samples were then viewed using a scanning electron microscope JSM-6390 SEM (JEOL, Tokyo, Japan).

#### 2.5. Growth Conditions Optimization

To optimize NaCl concentration and pH of the medium for growth of the *Mucilagibacter* strains, 50 µL precultures were added to 5 mL R2A liquid medium supplemented with 0–3% NaCl at pH 7, or to R2A without any NaCl and with pH set to the range between pH 2–11. Cultures were incubated at 28 °C for 7 days, after which culture turbidities optical density (OD) at 600nm were evaluated. Anaerobic growth was tested by incubating R2A plates in an anaerobic chamber at 28 °C for 1 week. Optimal growth temperature was tested in the incubator on R2A agar plates at temperatures between 4 to 40 °C for 1 week.

#### 2.6. Genomic DNA Extraction

Genomic DNA (gDNA) was extracted by using a TIANamp Bacteria DNA Kit (Tiangen Biotech, Beijing, China) from cultures grown on R2A. The quantity and purity of gDNA were assessed using an UV spectrophotometry (Nanodrop ND-1000, J & H Technology Co., Ltd. Wilmington, USA). Genomic DNA with OD<sub>260/280</sub> value higher than 1.80 was selected and examined on agarose gel electrophoresis (0.8%). Samples containing more than 25 µg of intact gDNA (fragment size > 20 kb) were sent out for whole-genome sequencing.

#### 2.7. Whole-Genome Sequencing

Whole-genome shotgun sequencing was performed using an Illumina HiSeq X Ten System provided by Vazyme Biotech Co., Ltd. (Nanjing, China). The DNA library was constructed using the Illumina V3 VAHTS Universal DNA Library Prep Kit according to the VAHTS Universal DNA sample preparation protocol (Illumina, Santiago, USA). The insert size was 300 bp for all strains, and 16,980,768, 18,531,104, 18,306,636, and 20,005,292 read-pairs and 2.86, 3.12, 3.09, and 3.37 Gb of raw data were obtained for strains *M. kameinonensis* P4 and *M. rubeus* P1, P2, and P3, respectively.

#### 2.8. De novo Genome Assembly and Annotation

Illumina reads were quality-filtered, trimmed, and de novo assembled with default settings using CLC Genomic Workbench 11.0 (QIAGEN, Hilden, Germany). The draft genome sequences were annotated by NCBI PGAP, and are accessible under GenBank numbers QEYR00000000, QFKW00000000, QFKV00000000, and QFKU00000000 for *M. kameinonensis* P4 and *M. rubeus* P1, P2, and P3, respectively. *M. kameinonensis* P4 generated 78 contigs with an n50 value of 350.607 bp. *M. rubeus* P1 generated 158 contigs with an n50 value of 139.339 bp. *M. rubeus* P2 generated 118 contigs with an n50 value of 132.524 bp. *M. rubeus* P3 generated 107 contigs with an n50 value of 148.541 bp.

#### 2.9. TraG Proteins Phylogenetic Analyses

Molecular phylogenetic analysis of TraG proteins was performed using MEGA6 [28]. The 807- to 850-amino acid sequences of TraG proteins were recovered from genome sequences of *Mucilagibacter* isolated in this study. The corresponding sequence in CTnDOT (TraG<sub>DOT</sub> accession number: AAG17832.1) was added to the dataset as an outgroup. Analyses were computed using an amino acid



Strain *M. kameinonensis* P4 displayed higher Cd resistance compared to strains *M. rubeus* P1, P2, and P3 (Table 2). Related, not heavy metal resistant *Mucilaginibacter pedocola* sp. TBZ30<sup>T</sup>, cultured under similar conditions displayed MICs of 0.4 mM Cu<sup>(II)</sup>, 3 mM Zn<sup>(II)</sup>, 0.2 mM Cd<sup>(II)</sup>, and 0.2 mM As<sup>(III)</sup> [33]. Such high resistance to multiple HMs as reported here has therefore not been observed before in the genus *Mucilaginibacter* [33].

**Table 2.** Minimal inhibitory concentration (MIC) of strains to Zn<sup>(II)</sup>, As<sup>(III)</sup>, Cd<sup>(II)</sup>, and Cu<sup>(II)</sup> and respective concentrations of the HM in the soil where the strains were isolated from.

Metals	<i>M. kameinonensis</i> P4	<i>M. rubeus</i> P3	<i>M. rubeus</i> P2	<i>M. rubeus</i> P1	<i>M. pedocola</i> sp. TBZ30 <sup>T</sup>
Zn <sup>(II)</sup> /mM	10.5	21.0	10.5	21.0	3.0
As <sup>(III)</sup> /mM	3.5	4.5	9.0	10.0	0.2
Cd <sup>(II)</sup> /mM	1.2	0.2	0.4	0.4	0.2
Cu <sup>(II)</sup> /mM	3.5	3.5	3.5	3.5	0.4
Zn/mg·kg <sup>-1</sup>	49.27	176.79	96.56	96.56	ND
Cd/mg·kg <sup>-1</sup>	1.21	1.19	2.26	2.26	ND
As/mg·kg <sup>-1</sup>	55.89	51.99	1.43	1.43	ND
Cu/mg·kg <sup>-1</sup>	365.10	1067.82	18.37	18.37	ND

Note. ND means not found.

Strains *M. rubeus* P1, P2, and P3 and *M. kameinonensis* P4 formed a light orange or pink, moist, circular, and convex colony with smooth margins on R2A agar plates. All strains were Gram-negative and aerobic. Growth of strains was observed at 4–30 °C (optimum, 28 °C). Optimal growth occurred in absence of further NaCl, but the strains could still grow in R2A with up to 1.5% NaCl added. These characteristics are consistent with description of the genus *Mucilaginibacter* [34–36]. Medium pH for optimal growth (~pH 5.0) and pH tolerance (pH 5.0–9.0) varied slightly between the four strains (Table 3).

**Table 3.** General features of strains *M. rubeus* P1, P2, and P3 and *M. kameinonensis* P4.

Property	<i>M. kameinonensis</i> P4	<i>M. rubeus</i> P3	<i>M. rubeus</i> P2	<i>M. rubeus</i> P1	<i>M. pedocola</i> sp. TBZ30 <sup>T</sup>
Gram strain	Negative	Negative	Negative	Negative	Negative
Cell shape	Rod-shaped	Rod-shaped	Rod-shaped	Rod-shaped	Rod-shaped
Colony colour	Light-yellow	Pink	Pink	Pink	Pink
pH	5.0–7.0 (5.0)	5.0–9.0 (5.0)	5.0–8.0 (5.0)	5.0–8.0 (6.0)	5.0–8.5 (7.0)
Temperature range (°C)	4–37 (28)	4–37 (28)	4–37 (28)	4–37 (28)	4–28 (25)
Oxygen requirement	Aerobic	Aerobic	Aerobic	Aerobic	Aerobic
Salinity (%)	0–1.5 (0)	0–1.0 (0)	0–1.5 (0)	0–1.0 (0)	0–1.0 (0)

### 3.3. *Mucilaginobacter* Strains Exhibit an Arsenal of Genetic Determinants to Deal with High Concentrations of Heavy Metals

To gain insight in the genetic basis of how the four strains were able to deal with these high HM concentrations, we determined draft genome sequences. Draft genomes were automatically annotated through RAST (Rapid Annotation using Subsystem Technology) database (<http://rast.nmpdr.org/>). Based on inferred protein homologies, between 6 and 16 putative P<sub>1B</sub> type-ATPase [37] were encoded in the four genomes (Table 4). All strains further encoded a variety of putative RND type metal transporter systems of the CzcCBAD type. Three strains further encoded putative CusCBA Cu<sup>(I)</sup> translocating RND-type transport systems, except *M. kameinonensis* P4 (Table 3). Multiple genes for putative multicopper oxidases were found on the different genomes, which may constitute the basis for the observed copper resistance (Table 3). Genes for putative multicopper oxidases were only taken into account if they were located adjacent to genes encoding P<sub>1B</sub> type Cu<sup>(I)</sup> translocating P-type ATPase. Finally, between 2 and 4 putative *ars* operons (*arsNCR*, *acr3*, *arsMCR*) were among the *Mucilaginibacter*

genomes (Table 3). The higher number of *ars* operons in strain P1 and P2 genomes correlated to their high MICs on As<sup>(III)</sup> (10.0 and 9.0 mM, respectively).

The number of HMR determinants in *Mucilaginibacter* genomes was unusually high, even in comparison to the well-known HM-resistant strain *Cupriavidus metallidurans* CH34 [5,38,39] (Table 4), suggesting a strong selection for HM resistance in their natural living environment. The HM resistance determinants are often clustered together, and often located adjacent to *tra* genes. They could be identified on many different contigs.

**Table 4.** Heavy metal related genes in the analyzed *Mucilaginibacter* strains in comparison to *Cupriavidus metallidurans* CH34.

Genes Encoding Heavy Metal Resistance Determinants		<i>M. kameinonensis</i> P4	<i>M. rubeus</i> P3	<i>M. rubeus</i> P2	<i>M. rubeus</i> P1	<i>C. metallidurans</i> CH34
P <sub>1B</sub> -type-ATPase	P <sub>1B-1</sub> type-ATPase	3	6	6	6	7
	P <sub>1B-3</sub> type-ATPase	1	4	5	4	0
	P <sub>1B-4</sub> type-ATPase	2	2	4	4	1
	Mg <sup>(II)</sup>	0	1	1	1	0
RND type metal transport systems	CzcCBAD	8	10	10	11	9
	CusCBA	0	2	4	3	2
	NccCBA	0	0	2	2	1
<i>ars</i> operons		2	3	4	4	1
Multicopper oxidases		2	6	5	6	2

RND: Resistance-nodulation-division.

### 3.4. Heavy Metal Resistance Is Associated with CTnDOT-Related Genomics Islands

Tolerance to HMs is frequently acquired by horizontal transmission among and between bacterial populations. Given the important size of HMR clusters identified in *Mucilaginibacter* genomes (up to 150 kb), we wondered whether some might be encompassed by GIs (Figure 2). We examined the close vicinity of the HMR clusters for the hallmark of conjugative systems, also known as Type 4 secretion systems (T4SSs) [40]. T4SSs have been classified based on their VirB4 protein, a ubiquitous constituent of conjugative systems [41]. A total of 17 genes encoding VirB4 proteins (*traG*) exhibiting sizes between 807 to 850 amino acids were identified on the 4 genomes, most of them in the close proximity of HMR clusters: 6 in *M. rubeus* P1 (contigs 1, 4, 24, 29, 42, 55), 6 in *M. rubeus* P2 (contigs 24, 26, 29, 32, 34, 42), 2 in *M. rubeus* P3 (contigs 5 and 11), and 3 in *M. kameinonensis* P4 (contigs 6, 9, and 35).

TraG proteins of the putative conjugative GIs identified in *Mucilaginibacter* genomes were compared to the 838-amino acid TraG of CTnDOT (TraG<sub>DOT</sub>) and showed 32 to 53% of identity over 94 to 98% of their amino acid sequence. The evolutionary history of TraG proteins was inferred using TraG<sub>DOT</sub> as an outgroup (Figure 3). Two strongly supported clades were delineated, suggesting that they belong to two distinct lineages (Figure 3, green and red boxes). As expected, each one of the TraG proteins of strain *M. rubeus* P1 grouped with one TraG protein from strain *M. rubeus* P2, confirming that these identical strains contain the same 6 elements. More interestingly, TraG<sub>P1-1</sub>, TraG<sub>P2-26</sub>, TraG<sub>P3-5</sub>, and TraG<sub>P4-9</sub> grouped together, and their gene sequences were identical.

Closer analysis revealed the presence of genes coding for other T4SS subunits adjacent to each one of the *traG* genes. This grouping of *tra* genes may be regarded as a conjugation module, i.e., genes and sequences implicated in the same biological process [42]. In particular the regions including *traG*<sub>P1-1</sub>, *traG*<sub>P2-26</sub>, *traG*<sub>P3-5</sub>, and *traG*<sub>P4-9</sub> were 100% identical across a circa 150-kb region, including an about 75-kb cluster coding for multiple HMR. The organization of these putative conjugation modules resembles the one encoded in CTnDOT, a prototypical ICE of *Bacteroides* [41,43]. As in CTnDOT, putative conjugative modules encoded by GIs of *Mucilaginibacter* thus belong to the mating pair formation (MPF) category B (MPFB) [41]. Also, most of the putative conjugative modules identified in *Mucilaginibacter* strains are in the proximity of genes encoding a putative tyrosine recombinase related to IntDOT, the integrase of CTnDOT [44]. Moreover, the *Mucilaginibacter* GIs carried a gene predicted to encode a RteC-like protein reminiscent of the CTnDOT regulation system [45,46]. *Mucilaginibacter*

GIs are thus likely to be ICEs, whose maintenance relies on integration into the chromosome and dissemination depends on its excision from the chromosome as a circular element that would transfer by conjugation [17,47,48]. The presence of at least one identical contiguous region over 150 kb (represented by the *tra<sub>GP1-1</sub>* gene) in the four different *Mucilaginibacter* recovered strains suggest active mobility and recent transfer of this GI.







*Mucilaginibacter* genomes did not give other perfect hits, suggesting that presence of this GI is restricted to sampling locations of this study (Table 1). Increasing availability of fully sequenced genomes should allow further data meaning in order to evaluate the abundance of specific GIs in *Mucilaginibacter* and predict their functionality.

The presence of putative CTnDOT-related ICEs into genomes of *Mucilaginibacter* strains does not seem uncommon. Protein BLAST analysis using TraG<sub>DOT</sub> as query and searching *Mucilaginibacter* genomes gave multiple hits with identity ranging from 70% over 99% of aa sequence, down to 30% over 79% of aa sequence (considering 96 hits with more than 75% of coverage). This observation highlights the presence of multiple putative CTnDOT-related GIs populating *Mucilaginibacter* genomes, most likely playing a key role in their genome evolution and adaptation. One can speculate that such GIs may be involved in conferring specific capabilities such as the ability to degrade pectin, xylan, and laminarin of *M. paludis* and *M. gracilis* [50] plant growth promotion capacity conferred by *M. gossypii* and *M. gossypiicola* [51], or yet to be discovered adaptive functions that may be conferred by such GIs. Further *in silico* analyses may reveal interesting features of such putative ICEs considering accessory functions they could confer, or functionality of their recombination, conjugation, or regulatory systems.

This exploratory work on HMR GIs of *Mucilaginibacter* together with other research done on *Mucilaginibacter* species so far constitutes a solid ground for future experimental research aiming at developing molecular tools. Such tools would greatly facilitate further investigation of *M. rubeus* and *M. kameinonensis* biology and could likely be extended to other *Mucilaginibacter* species.

**Author Contributions:** Y.P.L. isolated strains from mine and generated the phylogenetic tree of 16SrDNA, annotated the genome, mapped the gene cluster, and partially drafted the manuscript. N.C. contributed to the general concept of the study, performed gene sequence prediction, molecular phylogenetic analysis of TraG proteins, and partially drafted the manuscript. N.Y. contributed to the MICs determination and partially drafted the manuscript. B.L. performed growth conditions optimization and genomic DNA extraction. X.X. assembled the genomes. Q.S. and H.A.Al-W. contributed to data analysis. R.F. contributed to the general concept of the study and manuscript verification. J.R.v.d.M. contributed to the general concept of the study and manuscript verification. C.R. contributed to the general concept of the study, design of experiments and manuscript preparation.

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## References

1. Chandrangsu, P.; Rensing, C.; Helmann, J.D. Metal homeostasis and resistance in bacteria. *Nat. Rev. Microbiol.* **2017**, *15*, 338–350. [[CrossRef](#)] [[PubMed](#)]
2. Nguyen-Viet, H.; Gilbert, D.; Mitchell, E.A.D.; Badot, P.M.; Bernard, N. Effects of experimental lead pollution on the microbial communities associated with *Sphagnum fallax* (Bryophyta). *Microb. Ecol.* **2007**, *54*, 232–241. [[CrossRef](#)] [[PubMed](#)]
3. Huang, L.N.; Kuang, J.L.; Shu, W.S. Microbial ecology and evolution in the acid mine drainage model system. *Trends Microbiol.* **2016**, *24*, 581–593. [[CrossRef](#)] [[PubMed](#)]
4. Nies, D.H. Efflux-mediated heavy metal resistance in prokaryotes. *FEMS Microbiol. Rev.* **2003**, *27*, 313–339. [[CrossRef](#)]
5. Nies, D.H. The biological chemistry of the transition metal “transportome” of *Cupriavidus metallidurans*. *Metallomics* **2016**, *8*, 481–507. [[CrossRef](#)] [[PubMed](#)]
6. Reva, O.; Bezuidt, O. Distribution of horizontally transferred heavy metal resistance operons in recent outbreak bacteria. *Mob. Genet. Elem.* **2012**, *2*, 96–100. [[CrossRef](#)] [[PubMed](#)]
7. Llosa, M.; Gomis-Rüth, F.X.; Coll, M.; De la Cruz, F. Bacterial conjugation: A two-step mechanism for DNA transport. *Mol. Microbiol.* **2010**, *45*, 1–8. [[CrossRef](#)]

8. Cabezón, E.; Ripoll-Rozada, J.; Peña, A.; De la Cruz, F.; Arechaga, I. Towards an integrated model of bacterial conjugation. *FEMS Microbiol. Rev.* **2014**, *39*, 81–95. [[CrossRef](#)] [[PubMed](#)]
9. Monchy, S.; Benotmane, M.A.; Janssen, P.; Vallaey, T.; Taghavi, S.; Van der Lelie, D.; Mergeay, M. Plasmids pMOL28 and pMOL30 of *Cupriavidus metallidurans* are specialized in the maximal viable response to heavy metals. *J. Bacteriol.* **2007**, *189*, 7417–7425. [[CrossRef](#)] [[PubMed](#)]
10. Mergeay, M.; Monchy, S.; Vallaey, T.; Auquier, V.; Benotmane, A.; Bertin, P.; Taghavi, S.; Dunn, J.; van der Lelie, D.; Wattiez, R. *Ralstonia metallidurans*, a bacterium specifically adapted to toxic metals: Towards a catalogue of metal-responsive genes. *FEMS Microbiol. Rev.* **2010**, *27*, 385–410. [[CrossRef](#)]
11. Hernández-Ramírez, K.C.; Reyes-Gallegos, R.I.; Chávez-Jacobo, V.M.; Díaz-Magaña, A.; Meza-Carmen, V.; Ramírez-Díaz, M.I. A plasmid-encoded mobile genetic element from *Pseudomonas aeruginosa* that confers heavy metal resistance and virulence. *Plasmid* **2018**, *98*, 15–21. [[CrossRef](#)] [[PubMed](#)]
12. Bezuidt, O.; Pierneef, R.; Mncube, K.; Limamendez, G.; Reva, O.N. Mainstreams of horizontal gene exchange in enterobacteria: Consideration of the outbreak of enterohemorrhagic *E. coli* O104:H4 in Germany in 2011. *PLoS ONE* **2012**, *2*, 96–100.
13. Schneiker, S.; Keller, M.; Dröge, M.; Lanka, E.; Pühler, A.; Selbitschka, W. The genetic organization and evolution of the broad host range mercury resistance plasmid pSB102 isolated from a microbial population residing in the rhizosphere of alfalfa. *Nucl. Acids Res.* **2001**, *29*, 5169–5181. [[CrossRef](#)] [[PubMed](#)]
14. Gilmour, M.W.; Thomson, N.R.; Sanders, M.; Parkhill, J.; Taylor, D.E. The complete nucleotide sequence of the resistance plasmid R478: Defining the backbone components of incompatibility group H conjugative plasmids through comparative genomics. *Plasmid* **2004**, *52*, 182–202. [[CrossRef](#)] [[PubMed](#)]
15. Kamachi, K.; Sota, M.; Tamai, Y.; Nagata, N.; Konda, T.; Inoue, T.; Top, E.M.; Arakawa, Y. Plasmid pBP136 from *Bordetella pertussis* represents an ancestral form of IncP-1 $\beta$  plasmids without accessory mobile elements. *Microbiology* **2006**, *152*, 3477–3484. [[CrossRef](#)] [[PubMed](#)]
16. Guglielmini, J.; Quintais, L.; Garcillán-Barcia, M.P.; De la Cruz, F.; Rocha, E.P.C. The repertoire of ICE in prokaryotes underscores the unity, diversity, and ubiquity of conjugation. *PLoS Genet.* **2011**, *7*, e1002222. [[CrossRef](#)] [[PubMed](#)]
17. Carraro, N.; Burrus, V. The dualistic nature of integrative and conjugative elements. *Mob. Genet. Elem.* **2015**, *5*, 98–102. [[CrossRef](#)] [[PubMed](#)]
18. Carraro, N.; Rivard, N.; Burrus, V.; Ceccarelli, D. Mobilizable genomic islands, different strategies for the dissemination of multidrug resistance and other adaptive traits. *Mob. Genet. Elem.* **2017**, *7*, 1–6. [[CrossRef](#)] [[PubMed](#)]
19. Staehlin, B.M.; Gibbons, J.G.; Rokas, A.; O'Halloran, T.V.; Slot, J.C. Evolution of a heavy metal homeostasis/resistance island reflects increasing copper stress in enterobacteria. *Genome Boil. Evol.* **2016**, *8*, 811–826. [[CrossRef](#)] [[PubMed](#)]
20. Lee, S.; Ward, T.J.; Jima, D.D.; Parsons, C.; Kathariou, S. The arsenic resistance *Listeria* genomic island LGI2 exhibits sequence and integration site diversity and propensity for three *Listeria monocytogenes* clones with enhanced virulence. *Appl. Environ. Microbiol.* **2017**, *83*, 1189–11117. [[CrossRef](#)] [[PubMed](#)]
21. Al-Jabri, Z.; Zamudio, R.; Horvath-Papp, E.; Ralph, J.; Al-Muharrami, Z.; Rajakumar, K.; Oggioni, M. Integrase-controlled excision of metal-resistance genomic islands in *Acinetobacter baumannii*. *Genes* **2018**, *9*. [[CrossRef](#)] [[PubMed](#)]
22. Levings, R.S.; Partridge, S.R.; Djordjevic, S.P.; Hall, R.M. SGI1-K, a variant of the SGI1 genomic island carrying a mercury resistance region, in *Salmonella enterica* serovar Kentucky. *Antimicrob. Agents Chemother.* **2007**, *51*, 317–323. [[CrossRef](#)] [[PubMed](#)]
23. Carraro, N.; Matteau, D.; Luo, P.; Rodrigue, S.; Burrus, V. The master activator of IncA/C conjugative plasmids stimulates genomic islands and multidrug resistance dissemination. *PLoS Genet.* **2014**, *10*, e1004714. [[CrossRef](#)] [[PubMed](#)]
24. Carraro, N.; Durand, R.; Rivard, N.; Anquetil, C.; Barrette, C.; Humbert, M.; Burrus, V. *Salmonella* genomic island 1 (SGI1) reshapes the mating apparatus of IncC conjugative plasmids to promote self-propagation. *PLoS Genet.* **2017**, *13*, e1006705. [[CrossRef](#)] [[PubMed](#)]
25. Roberts, A.P.; Chandler, M.; Courvalin, P.; Guédon, G.; Mullany, P.; Pembroke, T.; Rood, J.I.; Smith, C.J.; Summers, A.O.; Tsuda, M.; et al. Revised nomenclature for transposable genetic elements. *Plasmid* **2008**, *60*, 167–173. [[CrossRef](#)] [[PubMed](#)]

26. Brosius, J.; Arfsten, U. Primary structure of protein L19 from the large subunit of *Escherichia coli* ribosomes. *Biochemistry* **1978**, *17*, 508–516. [[CrossRef](#)] [[PubMed](#)]
27. Chun, J.; Lee, J.H.; Jung, Y.; Kim, M.; Kim, S.; Kim, B.K.; Lim, Y.W. EzTaxon: A web-based tool for the identification of prokaryotes based on 16S ribosomal RNA gene sequences. *Int. J. Syst. Evol. Microbiol.* **2007**, *57*, 2259–2261. [[CrossRef](#)] [[PubMed](#)]
28. Tamura, K.; Stecher, G.; Peterson, D.; Filipski, A.; Kumar, S. MEGA6: Molecular evolutionary genetics analysis version 6.0. *Mol. Biol. Evol.* **2013**, *30*, 2725–2729. [[CrossRef](#)] [[PubMed](#)]
29. Kimura, M. A simple method for estimating evolutionary rates of base substitutions through comparative studies of nucleotide sequences. *J. Mol. Evol.* **1980**, *16*, 111–120. [[CrossRef](#)] [[PubMed](#)]
30. Felsenstein, J. Confidence limit on phylogenies: An approach using the bootstrap. *Evolution* **1985**, *39*, 783–791. [[CrossRef](#)] [[PubMed](#)]
31. Edgar, R.C. Muscle: Multiple sequence alignment with high accuracy and high throughput. *Nucl. Acids Res.* **2004**, *32*, 1792–1797. [[PubMed](#)]
32. Jones, D.T.; Taylor, W.R.; Thornton, J.M. The rapid generation of mutation data matrices from protein sequences. *Bioinformatics* **1992**, *8*, 275–282. [[CrossRef](#)]
33. Tang, J. Identification and Genome Analysis of *Mucilaginibacter pedocola* sp. nov. Ph.D. Thesis, Huazhong Agriculture University, Wuhan, China, 2017.
34. Liu, Q.; Siddiqi, M.Z.; Kim, M.S.; Kim, S.Y.; Im, W.T. *Mucilaginibacter hankyongensis*, sp. nov. isolated from soil of ginseng field Baekdu mountain. *J. Microbiol.* **2017**, *55*, 525–530. [[CrossRef](#)] [[PubMed](#)]
35. Kim, M.M.; Siddiqi, M.Z.; Im, W.T. *Mucilaginibacter ginsenosidivorans*, sp. nov. isolated from soil of ginseng field. *Curr. Microbiol.* **2017**, *74*, 1–7. [[CrossRef](#)] [[PubMed](#)]
36. Tang, J.; Huang, J.; Qiao, Z.; Wang, R.; Wang, G. *Mucilaginibacter pedocola* sp. nov. isolated from a heavy-metal-contaminated paddy field. *Int. J. Syst. Evol. Microbiol.* **2016**, *66*, 4033–4038. [[PubMed](#)]
37. Purohit, R.; Ross, M.O.; Batelu, S.; Kusowski, A.; Stemmler, T.L.; Hoffman, B.M.; Rosenzweig, A.C. Cu<sup>+</sup>-specific CopB transporter: Revising P<sub>1B</sub>-type ATPase classification. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 2108–2113. [[CrossRef](#)] [[PubMed](#)]
38. Mergeay, M.; Nies, D.; Schlegel, H.G.; Gerits, J.; Charles, P.; Van Gijsegem, F. *Alcaligenes eutrophus* CH34 is a facultative chemolithotroph with plasmid-bound resistance to heavy metals. *J. Bacteriol.* **1985**, *162*, 328–334. [[PubMed](#)]
39. Janssen, P.J.; Van Houdt, R.; Moors, H.; Monsieurs, P.; Morin, N.; Michaux, A.; Benotmane, M.A.; Leys, N.; Vallaeys, T.; Lapidus, A.; et al. The complete genome sequence of *Cupriavidus metallidurans* strain CH34, a master survivalist in harsh and anthropogenic environments. *PLoS ONE* **2010**, *5*, e10433. [[CrossRef](#)] [[PubMed](#)]
40. Christie, P.J. The mosaic type IV secretion systems. *EcoSal Plus* **2016**, *7*, 1–22.
41. Guglielmini, J.; Néron, B.; Abby, S.S.; Garcillánbarcia, M.P.; Cruz, F.D.L.; Rocha, E.P.C. Key components of the eight classes of type IV secretion systems involved in bacterial conjugation or protein secretion. *Nucl. Acids Res.* **2014**, *42*, 5715–5727. [[CrossRef](#)] [[PubMed](#)]
42. Toussaint, A.; Merlin, C. Mobile elements as a combination of functional modules. *Plasmid* **2002**, *47*, 26–35. [[CrossRef](#)] [[PubMed](#)]
43. Johnson, C.M.; Grossman, A.D. Integrative and conjugative elements (ICEs): What they do and how they work. *Annu. Rev. Genet.* **2015**, *49*, 577–601. [[CrossRef](#)] [[PubMed](#)]
44. Shoemaker, N.B.; Wang, G.R.; Salyers, A.A. NBU1, a mobilizable site-specific integrated element from *Bacteroides* spp. can integrate non-specifically in *Escherichia coli*. *J. Bacteriol.* **1996**, *178*, 3601–3607. [[CrossRef](#)] [[PubMed](#)]
45. Park, J.; Salyers, A.A. Characterization of the *Bacteroides* CTnDOT regulatory protein RteC. *J. Bacteriol.* **2011**, *193*, 91–97. [[CrossRef](#)] [[PubMed](#)]
46. Cheng, Q.; Sutanto, Y.; Shoemaker, N.B.; Gardner, J.F.; Salyers, A.A. Identification of genes required for excision of CTnDOT, a *Bacteroides* conjugative transposon. *Mol. Microbiol.* **2001**, *41*, 625–632. [[CrossRef](#)] [[PubMed](#)]
47. Delavat, F.; Miyazaki, R.; Carraro, N.; Pradervand, N.; Van der Meer, J.R. The hidden life of integrative and conjugative elements. *FEMS Microbiol. Rev.* **2017**, *41*, 512–537. [[CrossRef](#)] [[PubMed](#)]
48. Carraro, N.; Burrus, V. Biology of three ICE families: SXT/R391, ICEBs1, and ICES<sub>t1</sub>/ICES<sub>t3</sub>. *Microbiol. Spectr.* **2014**, *2*. [[CrossRef](#)]

49. Wood, M.M.; Gardner, J.F. The integration and excision of CTnDOT. *Microbiol. Spectr.* **2015**, *3*. [[CrossRef](#)]
50. Pankratov, T.A.; Tindall, B.W.; Dedysh, S.N. *Mucilaginibacter paludis* gen. nov. sp. nov. and *Mucilaginibacter gracilis* sp. nov. pectin-, xylan- and laminarin-degrading members of the family *Sphingobacteriaceae* from acidic *Sphagnum* peat bog. *Int. J. Syst. Evol. Microbiol.* **2007**, *57*, 2349–2354. [[CrossRef](#)] [[PubMed](#)]
51. Madhaiyan, M.; Poonguzhali, S.; Jungsook, L.; Senthilkumar, M.; Lee, K.C.; Sundaram, S. *Mucilaginibacter gossypii* sp. nov. and *Mucilaginibacter gossypicola* sp. nov. plant-growth-promoting bacteria isolated from cotton rhizosphere soils. *Int. J. Syst. Evol. Microbiol.* **2010**, *60*, 2451–2457. [[CrossRef](#)] [[PubMed](#)]



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